TI-935

WADC TECHNICAL REPORT 53-151

AD 014005

[redacted] ?

~~ASAPRL~~

STUDY OF HARD COATING FOR ALUMINUM ALLOYS

F. G. GILLIG
CORNELL AERONAUTICAL LABORATORY, INC.

MAY 1953

Statement A
Approved for Public Release

WRIGHT AIR DEVELOPMENT CENTER

AF-WP-(B)-O-6 JUL 53 250

20030610033

ASD 87 1843

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The information furnished herewith is made available for study upon the understanding that the Government's proprietary interests in and relating thereto shall not be impaired. It is desired that the Judge Advocate (WCJ), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, be promptly notified of any apparent conflict between the Government's proprietary interests and those of others.

WADC TECHNICAL REPORT 53-151

STUDY OF HARD COATING FOR ALUMINUM ALLOYS

F. G. Gillig
Cornell Aeronautical Laboratory, Inc.

May 1953

Materials Laboratory
Contract No. AF 18(600)-98
RDO No. 615-14

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Cornell Aeronautical Laboratory, Incorporated, Buffalo, New York, under USAF Contract No. AF 18(600)-98. The contract was initiated under Research and Development Order No. 615-14, "Aluminum Alloys," and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. J. C. McGee acting as project engineer.

ABSTRACT

A study has been made of the effects of hard oxide coatings produced by the MHC process on the properties of five wrought and two cast aluminum alloys. Coating thicknesses ranging from 0.0005 inch to 0.005 inch were studied. Of the many properties that were studied, the abrasion resistance of the coatings and their effect on the fatigue strength of the parent metal are the most significant. The abrasion resistance of the hard coatings is far in excess of that of coatings produced by standard anodizing treatments and has been demonstrated to be equal to or better than that of thin cyanide coatings on steel. In addition to this, the coatings impart increased corrosion resistance to the aluminum alloy surface. The abrasion resistance decreases with exposure to humidity and atmospheric conditions but proper post-treatments, other than boiling water which is used for sealing regular anodized coatings, will undoubtedly prevent this. The most serious shortcoming of the coatings has been found to be their drastic lowering of the fatigue strength of the coated alloy. Decreases as much as 65% in the base metal fatigue strength have been found. The effect is not proportional to coating thickness and coatings of 0.001 inch produce practically the same effect as 0.005-inch coatings.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. Sorte for

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

Figure

LIST OF ILLUSTRATIONS (CONT'D)

Figure

INTRODUCTION

The light weight per unit volume of aluminum is desirable in many applications where its wear resistance prohibits its use. Aluminum might also be desirable in some applications because of the ease of fabrication and its availability in a wide range of extruded sections. On the other hand, the weight or susceptibility to corrosion of case hardened steel make its use undesirable for the same applications.

A solution to this dilemma evidently lies in a method for producing on aluminum a surface which is comparable to that of case hardened steel. During the past few years, several processes for the production of hard oxide films on aluminum and its alloys of greater thicknesses than can be formed by the regular anodizing processes have made their appearance. These processes were welcomed by many designers as the solution to their problems. Because of the newness of the processes, little data other than the effect of the coating on wear resistance were readily available.

With many new processes the too eager acceptance and over application by designers had led to an early misuse and resultant adverse criticism which has been difficult to overcome. This has resulted in a general reluctance on the part of others to make use of these processes even for those applications to which they are ideally suited. In order to prevent this from occurring and to make available as much data on the properties of the hard coatings as possible in a relatively short time after their introduction, the Wright Air Development Center sponsored this test program under contract number AF 18(600)-98 to investigate the effects of hard coatings on the properties of aluminum alloys and to obtain design data which may be applicable to aircraft and guided missiles. The results of this program are presented herein together with most of the other data that have been published regarding the processes for producing hard oxide films on aluminum and its alloys.

PATENT HISTORY

The processes for producing a hard, wear and corrosion resistant film on aluminum by treating it electrochemically date back to the original development of the chromic acid anodizing process by Bengough and Stuart in 1924 (1, 2).* Since that time a number of variations of the process have evolved and some patents issued. A patent history and digest for the anodizing process has been assembled by G. H. Hogaboon which covers the state of the art up to 1945 (3). Most of these patents have expired and only a few are still in effect. The general features of these processes are similar and all aim toward the production of an adherent oxide on the surface of aluminum. The processes generally employ direct current and have the work piece as the anode. A few utilize alternating current and the coating forms only during that part of the cycle that the work piece is the anode. A number of electrolytes have been suggested but only a few have gained wide popularity: Chromic acid and sulphuric acid solutions for producing the commercial wear resistant films and oxalic and other acid solutions for use in the manufacture of electrolytic condensers. By controlling the concentration and composition of the electrolyte, and voltage conditions, coatings of various thicknesses and of varying porosities can be obtained. The thickness range is, however, limited to coatings below 0.001 inch, the usual commercially produced thickness lying in the range of 0.0001 to 0.0008 inch.

Within the past two years three processes have been developed for producing thick oxide coatings on aluminum which range up to 0.005 inch and greater in thickness. These processes are: The MHC (Martin Hard Coat) process, the Alumilite Hard Coating process, and the Hardas process. The first of these processes was developed at the Glenn L. Martin Company, Baltimore, Maryland. The patent application (4) has since been acquired by the Aluminum Company of America who developed the Alumilite Hard Coating process. The latter process has not received any wide publicity to date. No specific patent application has been made for this process but it is in general similar to the MHC process and is therefore covered by that patent application. It is also claimed that some of the features are covered by existing patents for the Alumilite process of sulphuric acid anodizing. The Aluminum Company of America plans to grant royalty free licenses to prospective users of both the MHC and Alumilite Hard Coating processes. The Hardas process is owned by Hard Aluminum Surfaces Ltd., Glasgow, Scotland.

*See bibliography.

LITERATURE SURVEY

All of the processes for producing a hard coating on aluminum and its alloys are electrochemical in nature and result in the formation of a thick layer of aluminum oxide on the surface of the article being treated. The main difference between normal anodizing and these processes is that they are performed at higher current densities and the process is carried out at low temperatures with considerable agitation. The exact processing details of the MHC and Hard Alumilite processes have not been released for publication but a number of articles have appeared in periodicals regarding the relative merits and properties of the MHC films (5-9). A paper was presented in February, 1952 by W. J. Campbell before the Institute of Metal Finishing in Birmingham, England relative to the Hardas process and the production of thick oxide films in general (10). Campbell states that the thick oxide films may be produced under a range of conditions and gives data for the variables, as follows:*

Electrical Requirements

Current density may vary from 0.1 ampere per square inch in an oxalic acid electrolyte to 3 amperes per square inch in sulphuric acid. In the Hardas process both direct and alternating currents are used: the proportion and actual voltages depending largely upon the material being treated and the desired thickness of the oxide film, the required voltage increasing as the film becomes thicker in order to maintain the current density at a constant value. Light alloys high in zinc may be treated with direct current only at 0.5 ampere per square inch in sulphuric acid at a starting voltage of 20 volts, rising to 50 volts in 15 minutes, producing a film 0.003 inch thick. An additional process is necessary with these alloys to improve the adhesion of the film to the metal. Die cast 13% silicon alloy is treated in sulphuric acid with a current density of 1.0 ampere per square inch and a large A.C. component. A 15% copper alloy has been successfully treated by applying A.C. alone for a short period to form a film and then finishing with suitably combined currents.

Proportions of A.C. and D.C. vary according to the alloy and, in most cases, it is necessary to preserve a constant voltage ratio between them during the whole processing period while the voltage is being raised to maintain constant current density. Several reasons are advanced for the need of a high current density. Some alloys require it to overcome

*It is to be noted that certain of the features enumerated in the paragraphs describing the Hardas processing are the basis of the Hard Aluminum Surfaces Ltd. patent applications.

passivity; also shorter time cycles may be used. The shorter the processing schedule the harder the surface that is produced. The electrolyte has a solvent action on the coating and the porosity of the coating increases the longer this reaction is allowed to proceed.

As may be inferred from the above, a relatively involved power setup is required for the Hardas process which uses a combination of A.C. and D.C. currents. (For comparison, the MHC process and the Hard Alumilite process require the use of D.C. current only.)

Chemical Requirements

Both oxalic acid and sulphuric acid can be used as electrolytes. Mixtures of the two have also been successful. The film produced by oxalic acid is generally smoother than that produced in sulphuric acid baths but the latter allows a higher production rate. Acid concentration is not critical; in fact, hard surfaces have been obtained in sulphuric acid baths ranging from 1% to 70%.

Temperature Control

Because of the high current densities involved and the tendency toward burning, the electrolyte must be maintained at a low temperature. The thicker the film the greater the amount of refrigeration that is needed. As the film builds up, its electrical resistance increases and the voltage must be increased to maintain the current density; this results in greater heat input and requires more refrigeration to maintain the electrolyte at a temperature which will prevent burning. Heat transfer is also increased by agitation of the solution and movement of the work rod. Optimum temperatures for sulphuric acid electrolytes seem to lie between -4°C and +4°C. As the temperature of the electrolyte increases above the upper limit, the film becomes progressively softer and there is apparently no definite line of demarcation between "hard" anodizing and "normal" anodizing.

Other Processing Variables

The process must be modified according to the aluminum alloy treated. It is preferable to process only one alloy at a time. Segregation in castings between heavy and light sections sometimes causes roughness and this defect has even been encountered in extrusions because of inhomogeneity in the extrusion billet. A thick piece of metal may have to be treated one way while a thin sheet of the same alloy may require modification of the process. This is due to the difference in heat dissipating properties of thick and thin sections.

CHARACTERISTICS AND PROPERTIES OF HARD COATINGS

Nature of Film

The film is basically aluminum oxide produced by electrochemical oxidation at the metal surface and it is integrally bonded to the base metal. The color of the film depends upon the alloy being treated and ranges from light to dark gray.

Thickness

Coating thicknesses up to 0.006 inch have been produced by the MHC process and 0.010 inch has been exceeded by the Hardas process. These are in contrast to standard anodizing which ranges from 0.0001 to 0.0008 inch. Although the very thick hard coatings mentioned above have been produced experimentally, the thickness recommended for most applications lies between 0.002 inch and 0.004 inch.

Alloys That May Be Coated

The MHC finish may be applied to aluminum and its alloys containing less than 5% Cu either in the wrought or cast form. The order of preference for resistance to abrasive wear is as follows:

Wrought		Cast	
1.	61S	1.	645
2.	75S Alclad	2.	220
3.	75S	3.	355
4.	24S Alclad	4.	356
5.	14S Alclad	5.	195
6.	52S		
7.	2S		
8.	24S		
9.	14S		

Alloys other than those listed have not been tested.

The Hardas process is not restricted to alloys containing less than 5% Cu for it is claimed that a 15% Cu alloy has been successfully treated.

Growth in Processing

The growth in processing is probably dependent upon the particular conditions used. Values reported for the MHC process are as follows:

Film Thickness In.	Growth In.
0.0004	0.00035
0.0008	0.00075
0.0020	0.0011
0.0044	0.0015

Parts must be machined undersize to allow for this growth in processing. It may be possible to reclaim some worn parts by applying the hard coating.

Selective Coating

Coatings are normally applied only to finished parts. Surface finish is generally maintained during the coating process. When specific areas are to be hard coated, and the rest of the part anodized, the entire part is first anodized and then properly masked before hard coating. Care must be taken in the masking operation as the flow patterns set up in the electrolyte and the insulating properties of the stop-off material may result in local burning of the hard coating.

Adherence

The film is strongly adherent to most alloys, especially those containing magnesium. The poorest adherence is shown with the alloys containing zinc. On right angle bends over a 3/4 inch rod, a 0.002 inch MHC coating will spall off on the compression side and forms fine cracks on the tension side. The coating has fair impact resistance although it is easily dented and slightly chipped when struck by a hammer repeatedly.

Abrasion and Wear Resistance

The best abrasion resistant coatings are produced on smooth surfaces. Wear resistance of the MHC coatings, as measured by a Taber Abraser, is better than case hardened steel and hard chrome plate. The comparison is illustrated by the data shown graphically in Figure 1. An added advantage of the thick oxide coatings is that the wear is equally slight on whatever other metal rubs against the film. The wear resistance of a Hardas film was dramatically demonstrated by turning an aluminum rod with a lathe tool made from hard surfaced high strength aluminum alloy. The tool showed no wear and did not collapse until an attempt was made to use it on hard bronze.

Coefficient of Friction

Preliminary tests have indicated that the hard coatings have a lower coefficient of friction than the untreated metal. Sliding wear tests indicate that maximum wear resistance can be obtained with a lubricant of molybdenum sulfide or graphitic grease. The film possesses good oil retention qualities even though the finest colloidal graphite will not pass into the pores. The coefficient of friction will of course depend upon the prior surface finish of the part and may be further reduced by lapping or honing the hard film.

A Hardas film finished to about three microinches gave a coefficient of friction of 0.11. Breakdown of the hard films is generally caused by disintegration of the oxide layer brought about by excessive frictional heat. As the film is a good thermal insulator, the heat remains localized. Therefore, two hard coated surfaces should not be used where they rub together unless the relative motion is slow or intermittent.

Hardness

Accurate values have not been determined by indentation methods but the coating may be considered as approximately file hard. The hard surface will scratch window glass. For use where the film is so loaded as not to cause its collapse, the hardness may be considered as approximately that of nitrided steel. The film disintegrates under the action of point loading and heat. Drilling can be carried out fairly easily after a part has been processed. The film may also be filed away with a coarse file. A smooth file has little effect on flat surfaces.

Ductility

The coating itself is brittle and cracks easily but remains strongly bonded to the base metal. The coating process causes some loss of ductility in the tensile test of coated 0.060 inch 75S-T6 sheet. The tensile and yield strengths are only slightly reduced and this is in part due to the decrease in cross section of the base metal.

Endurance Strength

Coating produces a marked decrease in the endurance strength of 75S-T6 aluminum alloy, as shown in Figure 2.

Heat Resistance

Tests show that 24S sheet with a 0.002 inch hard coating will withstand an 1800°F Bunsen burner flame for one minute whereas the uncoated sheet blisters and warps considerably after 15 seconds.

Coefficient of Thermal Expansion

The coefficient of thermal expansion of the hard anodic films differs considerably from that of the base metal. Checking will occur in the thicker films (0.002 inch and greater) when temperatures exceed 200°F. However, the coating shows no tendency to spall, and the checking does not materially affect the corrosion resistance. It has been suggested (10) that hard coatings may be purposely crazed by heating to increase their porosity and provide channels for lubricant.

Corrosion Resistance

The hard coatings show improved corrosion resistance over conventional anodizing. Little corrosion was shown by a 0.002 inch coating after 14 months continuous exposure to atmospheric and salt water corrosion. The coating is resistant to most of the common chemicals but is attacked by strong acids and alkalies.

Electrical Conductivity

The hard coating is a nonconductor and acts as an insulator . Whereas standard anodize films break down at about 340 volts, the MHC coatings withstand a range of 500 to 3400 volts depending upon thickness. The breakdown voltage of a 0.003 inch Hardas film is reported as 20,000 volts.

Rain Erosion

Tests on the susceptibility of MHC coatings to erosion by rain were conducted at Cornell Aeronautical Laboratory, Inc. (11). The test specimens were mounted at the ends of a propeller which rotated at a speed that caused the specimens to strike a uniform rainfall at 500 m.p.h. The hard coating produced by the MHC process is the best inorganic coating that has been tested to date. Some comparative data are given below:

Alloy and Coating	Time to Initiate Erosion*	Time of Comparable Erosion
2S ½ H	4 min.	10 min.
24S-T6 Alclad	5 "	10 "
24S-T6	30 "	105 "

Alloy and Coating	Time to Initiate Erosion*	Time of Comparable Erosion
24S-T6 Anodized	30 min.	105 min.
FS-1H Magnesium	20 "	70 "
24S-T6 MHC Coating	45 "	120 "
Titanium	No erosion after 360 minutes	360 plus

*Time to produce as much erosion as that occurring on 24S-T3 Alclad when the cladding has just been worn through.

Cost

The cost of the hard coating films in electricity and chemicals per unit of thickness is little more than that of normal anodizing. However, these coatings are usually from four to ten times as thick as the ordinary films and the production costs per part are proportionately higher. The cost of setting up the process is higher due to the increased refrigeration equipment and provisions for agitation of the solution and movement of the work rod that are necessary. The Hardas process also requires a more elaborate electrical setup to provide both A.C. and D.C. current.

Applications

The hard coatings have been applied to the following items with a resultant improvement:

- aluminum bearing races
- gears and pinions
- surveying instrument parts
- impeller blades
- hand tools
- swivel joints
- friction locks
- leading edges of wings and airfoils

cams

aluminum jigs and fixtures

pistons

leg braces for paraplegics

jack screw threads

airplane door thresholds and walkways

carburetor deck plates

aircraft door hinges

Many direct substitutes of hard coated aluminum for steel in moving parts and static surfaces subjected to scuffing and other forms of wear have been made by the Glenn L. Martin Company in their aircraft.

TEST PROGRAM

All of the hard oxide coatings that were tested during this project were applied by the MHC (Martin Hard Coat) Process. The work was done at Cornell Aeronautical Laboratory, Inc. in an experimental tank containing 65 gallons of solution. Processing conditions were as specified in the Aluminum Company of America Bulletin No. 6 for Alcoa Finishes. Precleaning was done in hot 5% caustic followed by treatment in "DO" Deoxidizer, a proprietary compound produced by the Cowles Chemical Company.

The following alloys were included in the investigation:

61S-T6

XA78S-T6

Bare 24S-T4

Alclad 24S-T4

Bare 75S-T6

Cast 356-T6

Cast 220-T4

Coatings were applied on these alloys in thicknesses ranging between 0.0005 and 0.005 inch in thickness. The following properties of the coating and its effect on parent metal properties were studied:

Coating Thickness Time Relationships

Growth During Processing

Color of Coating

Coating Defects and Deficiencies

- Crazing
- Blisters
- Surface Roughness
- Corner Defect

Minimum Radii for Coating

Structure

Throwing Power

Abrasion Resistance

- As-coated
- After Exposure to Atmospheric Conditions
- After Exposure to High Humidity

Dielectric Strength

Fatigue Strength

Bend Radii

Flame Resistance

Heat Resistance

Thermal Conductivity

Tensile Strength

Compression Strength

Rain Erosion

Gunfire Penetration

Thermal Expansion

Corrosion Resistance

Atmospheric
Humidity
Salt Spray

These tests are fully described and the results presented in the next sections of this report.

TEST PROCEDURES AND RESULTS

Coating Thickness - Time Relationships

In order to be able to predict with a reasonable degree of assurance that a definite thickness of coating could be applied to a given alloy, it was first necessary to coat a series of test pieces for given lengths of time and determine the thicknesses of the resulting coatings. Specimens of each alloy were coated for 40, 100, and 200 minutes and the coatings measured microscopically (12, 13). Thickness vs. time curves were plotted and these were used to apply given thicknesses of coatings on the specimens to be tested. Small pieces were also cut from the first series of test specimens and the coating thicknesses measured to provide more points and better establish the curves. The thickness of coating vs. time curves are shown in Figure 3. It should be noted that the current density could not be maintained for the 61S alloy with the 130 volt generator which was used and this curve falls off for this reason. The 75S and XA78S alloys allow the coating to build up faster than the 24S bare or Alclad. Actual thicknesses close to 0.009 inch were measured for the 75S and XA78S alloys. However, in these greater thicknesses, the edges tend to crumble and the surface layers are soft and powdery.

The curves as presented in Figure 3 apply only for the coating conditions specified in the Aluminum Company of America Bulletin No. 6 for Alcoa Finishes and deviations from these conditions will influence the rate of coating and the maximum thickness obtainable.

Growth During Coating

The test specimens were accurately measured before and after coating and the increase in thickness obtained for the various coating thicknesses which were measured metallographically. These data are plotted for the various alloys in Figure 4. It can be seen that all of the alloys show a uniform growth equal to approximately one-half the thickness of the coating. This is to be expected inasmuch as the basic constituent of all of the coatings is the same.

Color of Coatings

The color of the coating depends both upon the alloy and upon the coating thickness. 61S and 24S bare and Alclad have a light tan or gray color for a 0.0005-inch coating which gradually darkens to a jet black as 0.003 inch is exceeded. The 75S and XA78S alloys have a light tan color when coated with 0.0005 inch which turns to jet black for 0.001 inch. The color then changes to a blue-gray which gets progressively lighter until at 0.009 inch the coating is almost white. On 99.99% purity aluminum, the coating is colorless for the 0.001-inch thickness and slowly changes to a light brown as the thickness is increased to 0.005 inch. The color of the coatings is also dependent upon the amount and type of alloy previously processed in the bath.

Coating Defects and Deficiencies

Crazing - or fine hairline cracks are present on the surface of the coating when it is withdrawn from the processing bath. These cracks occur during the processing cycle. As the coating warms up to room temperature, the number of cracks in the coating increases. If a coated piece is held near the ear, the cracking of the coating is audible. The cracks are not as clearly visible on the alloys that form dark gray and black coatings as they are on the transparent coatings formed on pure aluminum. Figure 5 shows the crazed pattern that developed on a piece of commercially pure aluminum.

Blisters - have been encountered in some of the 24S Alclad specimens. Their occurrence seems to be directly related to the ratio of the thickness of the coating to the thickness of the cladding. When the thickness of the hard coating exceeds the thickness of the cladding, blistering is liable to occur. Figure 6 shows a 0.004-inch coating on 0.031-inch sheet and on 0.082-inch sheet. The 0.031-inch sheet is badly blistered while the 0.082-inch sheet is uniformly coated. The cladding on the two sheets was 0.0022 and 0.0056 inch respectively. This defect seems to be associated with particular lots of material as other lots of this alloy have been processed which coated satisfactorily.

Surface Roughness - is increased when the 24S bare alloy is processed. It is not as pronounced in the case of sheet stock as it is in bar stock. The coating process seems to accentuate the macrostructure. However, this roughness can be eliminated if the part is made slightly oversize (allowing for increase in dimensions due to coating) and lapped down to the finish dimension after coating. Figure 7 shows a spool for a hydraulic valve before and after applying a 0.003-inch coating. The part was subsequently lapped and placed in an experimental valve which has outperformed the previously used stainless steel spools in all respects.

Corner Defect - The coating does not form satisfactorily at corners and has a tendency to crumble at these points. This is due to the nature of the mechanism of formation of the coating (14). The process is the reverse of electroplating in that the reaction proceeds inward from the surface of the piece being coated. As the coating is formed, the specific volume increases and a growth occurs. At corners, the coating is able to grow inward to some extent but the corner cannot expand in three directions and a void occurs as shown in Figure 8. The voids are not as pronounced in the thinner coatings as in the thicker ones.

Minimum Radii for Coating

Stepped specimens were turned from 61S alloy rod and coated with a 0.003-inch coating. The specimens were so made that the smallest diameter was 1/16 inch and the diameter of each successive step increased by 1/16 inch increments. The specimens were cut up after coating and cross sections of the various diameters examined metallographically. The number of cracks in the coating was counted for each diameter. Photographs of the cracks in two of the sections are shown in Figure 9. The data are tabulated below:

Diameter	Circumference	No. of Cracks	Cracks/Inch
1/16 Inch	0.196	36	184
1/8 "	0.393	28	71
3/16 "	0.590	25	42
1/4 "	0.785	27	34
(straight section)	1.125 long	12	11

If the cracks in the straight section are considered to be the result of expansion and normal processing conditions, then the number of cracks in excess of this number may be considered due to radial growth. As can be seen from the above data, even the fairly large radius of 1/8 inch (1/4 inch diameter) results in the formation of three times the number of voids present in a straight section. However, the coating on the 1/16-inch diameter was quite adherent and showed no tendency to crumble away as the coatings do on sharp corners. The question of minimum radii would, therefore, seem to be dependent upon the application. It is recommended that design radii be as large as permissible.

Structure of Coating

Metallographic examination of the coating revealed some features that show a close similarity between the hard coatings and regular anodize coatings as described by Edwards and Keller (15). Figure 10 shows the normal hard coating as it appears under polarized light. It consists of two layers which differ in some manner, at least in their reflection of polarized light. Under white light a photomicrograph of the coating appears to be quite uniform as seen in Figure 11. When examined visually under the microscope a hint of a subsurface layer is present but the contrast is insufficient to record it on a photographic plate. Figure 12 is a photomicrograph of the same field as shown in Figure 11 but illuminated with polarized light. This multilayered structure is peculiar to 24S bare alloy and seems to account for the anomalous behavior shown by the coating on this alloy in the various tests. Several layers are sometimes encountered in some of the coatings on the other alloys but these are fewer in number and related to the number of periodic voltage adjustments that are made during processing. These layers do not have the effect on the properties of the coating as displayed by the 24S alloy coatings.

Figure 13 shows the coating structure on the 356 casting alloy. The free silicon remains undisturbed during the coating process except for an expansion perpendicular to the coating-metal interface.

The coating formed during the MHC process is essentially aluminum oxide formed from the base metal and the oxygen liberated electrolytically at the metal surface. The coating being a non-conductor must, of necessity, be porous to allow the electrolyte to pass through it and reach the base metal. This porosity of anodic coating has been studied by Edwards and Keller (15) and shown to be of extremely minute dimensions.

Aluminum oxide is known to exist in a number of forms (16), each with distinct properties. The form of the oxide present on the aluminum surface will, therefore, control the properties of the surface. The films produced by the conventional anodizing processes are amorphous in nature unless formed under special conditions (14). Keller and Edwards (17) state that gamma-alumina has been observed by X-ray diffraction in anodic films formed on aluminum at 100 volts or higher (high current densities). It was thought that the hard coating would probably contain a fair proportion of gamma-alumina and this would account for the difference in properties between these coatings and the regular anodize coatings. This has not been proven to be the case. The coating was examined extensively by X-ray diffraction methods and these studies failed to reveal any crystalline structure in the coating. The following methods of diffraction analysis were employed:

1. The coating was chipped off by picking it with a knife or flexing the specimen. The chips were then ground to pass a 250 mesh screen. This powder was coated on hairs, packed in thin glass tubes, packed in washers, and formed into wedges. None of these techniques gave any results with exposures up to four hours when background fog became prohibitive.

2. Chips of the coating were exposed by transmission, back reflection and grazing angle shots off both sides of the coating.

3. In view of the polarized light showing a layer adjacent to the base metal, grazing angle shots were tried off of the base metal after the coating was spalled off by flexing. The aluminum background was too strong to pick up any lines which might have resulted from the coating which has a comparatively low absorption coefficient.

4. Back reflection technique was tried on coatings from 0.005 inch to 0.009 inch in thickness. When the coating became thick enough that no aluminum lines appeared, there was no structure present even with extremely long exposures.

The above methods have been enumerated in order to show the detail and thoroughness with which this part of the investigation was pursued.

The lack of evidence to the contrary indicates that the coating is amorphous in nature and the structure very similar to that of regular anodize coatings.

Throwing Power

In electroplating parlance, the ability of a plating procedure to deposit a uniform coating in deep recesses is known as "throwing power". In order to determine the throwing power of the MHC process, the following experiment was performed. Four tubes, two of each size, as tabulated below were closed at one end with rubber stoppers and coated. The tubes were sectioned and the inner and outer coating thicknesses measured at the center and both ends. The results for the pairs of tubes processed at the same time were averaged and the results are tabulated below:

61S-T6 small tubes 3/8 inch O.D. by 0.035 wall by 5 inches long.

	Outside Coating Thickness	Inside Coating Thickness
Open end	0.0045 inch	0.003 inch
Center	0.0045 inch	0.0015 inch
Closed end	0.0045 inch	0.0005 - 0.0008 inch (Coating appears to be burned and very porous.)

61S-T6 large tubes 5/8 inch by 0.049 wall by 5 inches long.

	Outside Coating Thickness	Inside Coating Thickness
Open end	0.0025 inch	0.0017 inch
Center	0.0025 inch	0.0016 inch
Closed end	0.0025 inch	0.0016 inch

The above conditions are extreme and very few plating solutions could plate more than an inch inside the smaller tube. The fact that the hard coat formed at the closed end of the tubes at all shows that it has extreme throwing power. The tests show that the thickness of the coating drops off even close to the tube mouth and it would appear to be desirable to use auxiliary cathodes and agitation inside deep recesses if a uniform and dense coating is desired at such points.

Abrasion Tests

The resistance of the hard oxide coatings to rubbing abrasion has been demonstrated to be better than that of hard chrome plate and cyanide hardened steel (7). The primary objective of the abrasion tests that were conducted for this investigation was to determine the effect of exposure to atmospheric conditions and high humidity on the abrasion resistance of the hard oxide coating. It has been shown by Arlt (18) that the abrasion resistance of regular anodized coatings is related to the degree of hydration. In order to determine the magnitude of this effect on heavy oxide coatings, a similar series of experiments was planned.

Two sets of test specimens representing the following coating thicknesses were prepared for each alloy:

0.0005 inch

0.001 inch

0.002 inch

0.003 inch

0.004 inch

0.005 inch

The coating thicknesses were accurately measured by means of the metallograph and the "as-coated" abrasion resistance determined on an Arlt

Abrasiometer (18). The abrasiometer is a device that causes a stream of abrasive particles, in this case 180 mesh Carborundum, to impinge upon the surface to be tested until the coating is worn down to the base metal. The abrasive stream is propelled by controlled air pressure and the end point is visual. A deviation from the test as used by Arlt on regular anodized coatings was made. The air pressure was increased to 20 cm. of mercury in order to accelerate the test and to approach a range in the pressure-air flow curve where the flow is less sensitive to pressure changes.

Two sets of abrasion specimens were prepared. One set was exposed on the outdoor exposure rack shown in Figure 14. The rack is located on the roof of the Cornell Aeronautical Laboratory which is in a semi-industrial atmosphere. The other set of specimens was placed in desiccators containing distilled water at 80-90°F. The abrasion resistances were checked at the end of 30, 60, and 90 days and 6 months. Check runs were made before and after each set of test runs on a standard specimen which was stored in a desiccator containing a desiccant. A minimum of three runs were made and averaged to obtain each point plotted on the curves shown in Figures 15 through 21. The as-coated abrasion resistance of the alloys increases uniformly with thickness with the exception of the 24S bare. In the as-coated condition 24S Alclad has a slightly better abrasion resistance than the other wrought alloys. The 356 cast alloy showed the highest abrasion resistance of all of the alloys tested. This may be due to the large amount of free silicon present in the alloy and which becomes entrapped in the coating. Figure 13 shows how the silicon inclusions remain undisturbed during the coating process except for an expansion perpendicular to the interface. The 220 alloy has a lower as-coated abrasion resistance than any of the other alloys tested with the exception of 24S bare.

There is a general decrease in the abrasion resistance of all of the alloys with increase in the time of exposure to both the atmospheric conditions and humidity. The decrease is greater under the high humidity conditions than it is under exposure to atmospheric conditions and in most cases is proportional to the thickness of the coating. This may be due to the condition mentioned previously, that the heavier coatings have a more porous outer layer because of the increased time of contact with the electrolyte which has a solvent action on the coating. The 24S bare shows wide scatter under all conditions and is not considered to be a suitable alloy for use with the hard coating processes when abrasion resistance is required.

Dielectric Strength

The dielectric strengths of the coatings on the five wrought alloys and the two casting alloys were determined according to A.S.T.M. Method B110-45 (19,20). The breakdown voltages for the different thicknesses are shown graphically in Figures 22 through 25. The two high strength alloys 75S and XA78S have the highest values with the casting alloys 356 and 220 having the lowest. The 24S bare data again show considerable scatter. The low values for the casting alloys are probably caused by the increased amount of inclusions in the oxide coating which are characteristic of cast alloys as compared to wrought alloys.

Some scatter was shown in the individual readings which were averaged to obtain the values plotted on the curves. If one considers the way the coating crazes, the reason for the scatter becomes apparent. When the electrode is placed directly over a crack, the dielectric strength becomes that of an air gap equal to the thickness of the coating.* The coating, for the same reason, and because of its inherent porosity, would not provide insulation in liquid electrolytes.

Effect of Coating on Fatigue Strength

Fatigue tests were conducted on Baldwin-Lima-Hamilton Model SF-2 constant load fatigue machines. The specimens were subjected to reversed bending until failure or 10 million cycles were exceeded. No attempt was made at statistical analysis of the data before plotting the curves as the trends are definite and unmistakable.

The calculation of the maximum fiber stress imposed upon the coated specimens during the bending fatigue tests presented a problem. It had already been determined that the coating was very brittle and was a maze of cracks. Because of this it was felt that the coating on the tension side of the specimen carried very little load. This was shown to be true by the tensile tests. On the compression side, after the cracks closed, the coating was capable of bearing a considerable load. It was also known that a growth occurs during processing which is equal to one-half the coating thickness. The fatigue specimens were coated on both sides so the total increase in thickness was equal to the thickness of the coating on one side. Disregarding the growth in the coating was, therefore, equivalent to neglecting the coating on one side of the specimen regardless of the coating thickness. The original specimen thickness was used in calculating the specimen stress for these reasons. As the data are used on a comparative basis, any small inaccuracies involved tend to cancel out.

Various combinations of coating thicknesses were tested on the different alloys and in the case of the 61S alloy three different sheet thicknesses were tested. Specimens coated on one side only and specimens coated for half the gage length were also run to determine the relative

*In those cases where the crack extends only partially through the coating, the result is a combination of the two dielectric strengths.

effects of these practices on fatigue life. The data from these tests are plotted in Figures 26 through 34, 36, 37, and 38.

The fatigue curve for 24S Alclad is shown in Figure 26. Points are plotted for the uncoated material and for 0.002 and 0.003-inch coatings. The coating lowers the endurance strength considerably at high stresses. At lower stresses, the curves tend to converge and the endurance strength at 500 million cycles would be affected by a relatively small amount. However, it should be kept in mind that the curve for the uncoated 24S Alclad is considerably lower than the curve for the 24S core alloy because of the ease of crack initiation in the low strength cladding. Figures 27, 28, and 29 show the drastic reduction in fatigue strength caused by the coatings on the high strength alloys 24S bare, 75S, and XA78S respectively. Increase in the thickness of the coating from 0.001 to 0.005 inch does not change the effect on the endurance strength noticeably. The first 0.001 inch of coating appears to have almost as drastic an effect as does increasing the coating thickness to 0.005 inch.

Data for 75S Alclad are given in Figure 30. In this case, the 0.001-inch coating does not appear to affect the endurance strength appreciably, while the 0.003-inch coating does. This trend was also shown by the 24S Alclad and may be due to the ability of the remaining soft cladding to resist crack propagation. However, the cladding itself reduces the endurance limit of both of the above alloys to a level which is relatively low compared to the unclad material, and the decrease in sensitivity to the coating is of little practical value where a high strength material is needed.

The 61S alloy was studied at greater length than the others. Three thicknesses of base metal with various thicknesses of coatings were tested for endurance strength. Another series of tests was run on this alloy with the coating on both sides for one-half the length. Other tests were made on specimens coated on one side only. These data for the 61S alloy are shown in Figures 31 through 36. The tests on three different base metal thicknesses show that coating thicknesses over 0.001 inch have little, if any, additional effect on the endurance strength. The main point that these tests were intended to show is that the decrease in endurance strength is not due entirely to a decrease in parent metal thickness due to the formation of the coating. Although there is an increase in the thickness of the parent metal remaining after coating of approximately 3 to 1 (0.029 inch to 0.077 inch), the endurance strength is unaffected for the same number of cycles. The decrease in endurance strength cannot be laid to the decrease in parent metal cross section and can be accounted for only by the stress concentrations at the microcracks in the coating.

The 61S specimens coated for one-half their length on both sides gave the data shown plotted in Figure 34. Comparison with the curve for the uncoated base metal shows the same order of decrease in endurance strength for these half-coated specimens as the specimens coated over their entire surface. It is believed that this is due to a stress concentration arising at the junction due to a change in the flexure curve of the specimens. This change in curvature is brought about because of the different modulus of elasticity of the coating. The location of the fatigue failures for this group of specimens is shown in Figure 35.

The 61S specimens coated on one side only also exhibit the same decrease in endurance strength as the specimens coated over their entire surface. These data are given in Figure 36. Evidently, the stress concentrations arising at the coating microcracks on one side of the specimen are sufficient to initiate failure.

The data presented in Figures 37 and 38 for the two casting alloys 220 and 356 show that the coating has little effect on the endurance strength. The wide scatter of data for cast specimens, because of their inherent inhomogeneities and somewhat open structure, yields a scatter band of increased width and a low endurance level to begin with. The addition of a few more additional stress raisers can be expected to have only a proportionate effect. In fact, it has been shown in some instances that a large number of stress raisers has less effect on the fatigue life than only a few. The coating can be used with comparative safety on these alloys if the initial low endurance strength can be tolerated.

The fatigue test results may be summarized in tabular form as given below:

Alloy	Endurance Strength at 10^6 Cycles in P.S.I. Uncoated	Coated	% Decrease
24S Alclad	11,000	7,500	32
24S Bare	19,000	15,000	21
75S	22,000	9,000	59
XA78S	26,000	9,000	65
75S Alclad	12,000	10,000	17
61S	15,000	6,000	60
220	7,500	7,500	0
356	8,000	8,000	0

The deleterious effect of the coating increases approximately as the strength level of the base metal. The 61S alloy is a little out of line as is the 24S bare which behaves abnormally in nearly all of the tests made.

Bend Tests

The wrought alloys 24S bare and Alclad, 75S, XA78S, and 61S with coating thicknesses ranging between 0.0005 inch and 0.005 inch were subjected to bend tests in order to determine the bend radii, adherence, and the effect of tension and compression loading on the coating. The specimens were approximately 1/16 inch thick by 1 inch wide by 8 inches long. Bending was accomplished by placing the specimen lengthwise between the jaws of a vise and screwing the vise jaws together. The free bend radius was checked by means of templates and pins of various radii. The coated surfaces were carefully watched for the first signs of failure of any kind. Failure occurred by flaking of the top layers in some cases, as shown in Figure 39. Other failures were by spalling off of the full thickness of the coating, as shown in Figure 40, and still others by a hairline spalling which gradually spread as the bend radius was decreased. The latter type of failure is shown in Figure 41. In all of the tests which were made, the coating failure always occurred on the compression side. On the thicker specimens, the coating sometimes checked along the edges of the tension side, but the remainder of the coating was visibly sound until base metal failure took place. The data for the bend tests are tabulated in Tables I through V.

Flame Tests

It has been reported in the literature (7) that the hard oxide coatings provide increased resistance to heat and high temperatures. In order to check this property, specimens four inches square were cut from the various alloys and hard coated with thicknesses from 0.000 to 0.005 inch. These specimens were mounted in a holder so that they were 6-1/2 inches away from the flame produced by a No. 5 tip on a Harris oxy-acetylene torch, Model No. 50. The flame was adjusted to neutral with the following settings: oxygen pressure, 15 pounds; acetylene pressure, 12 pounds; torch needle valves full open. All tests were run at the same time and the flame was not disturbed between tests. Specimens were changed by interposing a sheet of stainless steel between the flame and the holder and recording the time from the instant this sheet was removed. The pressure readings had not changed at the end of the test series. A "blank" sheet of the uncoated 61S alloy which was the first alloy to be tested was run after the last test and very close agreement was found. Two specimens were run for each thickness of coating on the wrought alloys. Only one specimen was run for the cast alloys. The duration of exposure to the flame was accurately measured with a stop watch. The end point of the tests was taken as the first visible sign of sagging as shown in Figure 42. In spite of the relative crudeness of the test method, duplicate runs gave surprisingly close checks. The results of these tests are given in Table VI.

Examination of the data shows that in nearly all cases the time to failure increased as the thickness of the coating increased. However, it should be pointed out that the specimens were merely held upright in a holder at right angles to the flame and the only stress imposed was that caused by thermal expansion and the pressure of the burning gases. The refractory oxide coating was unaffected by the flame and it was the parent metal which melted between the two oxide skins. The coating remained intact during all of the tests and showed no tendency to spall off due to the heat. As the thickness of the coating was increased, the ability to hold the molten metal in place also increased. If the coating was punctured with a scriber or wire after the specimens gave indications of failure, molten aluminum would flow out. It is believed, therefore, that strengthwise, the increase in time duration means very little and that coated and uncoated alloys would perform alike under stress.

The color of the coating might have an effect on the rate of heat absorption due to differences in reflectivity and thermal conductivity. This point was studied further by the series of heat tests which follow.

<u>Heat Tests</u>

A series of heat absorption tests was run to determine the effect of the various colors and coating textures obtained on the different alloys under investigation. These tests were conducted on 4-inch square specimens coated on both sides with coatings from 0.000 to 0.005 inch in thickness. The tests were conducted in the same manner as those made by Phillips (21) on anodized coatings.

A 28 gauge chromel-alumel thermocouple was cemented in a small 2-hole insulator with Sauereisen cement and filed flat on the end. This thermocouple was held against the back of the test specimen with a spring arrangement that insured intimate contact. Several previous runs had been made with the thermocouple firmly attached to the specimen by peening it into a hole and others by attaching the bead with Sauereisen cement. The above mechanical attachment was then devised so that it would closely duplicate the results of these fixed methods. The mechanical method was adopted because of the ease of changing specimens. The specimens were mounted six inches away from an infrared bulb and the output of the thermocouple read with a potentiometer until it became steady. Two or three runs were made on each combination of alloy and coating thickness. At the start of the tests, two infrared bulbs were standardized against each other and the second bulb used to check for deterioration of the one in use at intervals during the tests. The data from these tests are presented graphically in Figures 43 and 44.

The coated specimens attained a higher temperature than the uncoated ones in all cases. It was thought that the rate of temperature rise would be appreciably different for the alloys which showed considerable differences in color, such as 61S which becomes jet black upon coating as opposed to the 75S and XA78S alloys which are a light gray in the heavier coating thicknesses. This did not prove to be the case. It was therefore felt that, since the rates of temperature rise were approximately equal for equal thickness of sheet, the higher peak temperatures could be explained on the basis of the insulating value of the coating.

Thermal Conductivity

In order to check the relative thermal conductivities of the coated specimens, another series of tests was made in which the 4-inch square specimens were coated on one side only. These specimens were tested using the same procedure outlined above for the heat tests. The data are plotted in Figures 45 and 46. It can be seen that the curves for the coated specimens fall below those for the uncoated specimens in all cases when the insulating effect of the coating on the back side of the specimen is lost. Differences in the reflectivity of the surfaces, especially the 24S Alclad and volume of metal (XA78S was 0.064-inch thick, whereas the other alloys were 0.051-inch thick) would account for variations in the spread between the curves for the coated and uncoated specimens of the individual alloys. Although the above data are all qualitative in nature and the determination of physical constants has not been attempted, it can be inferred that the coating has a lower thermal conductivity than the base metal for all of the alloys tested. This would no doubt be true for any aluminum alloy. The wide color variation which exists between the coatings on the different alloys and even in different thicknesses of coating on the same alloy seems to have a relatively minor effect.

Effect of Coating on Tensile Strength

Tensile test specimens were machined from the wrought alloy sheets to give a 2-1/2 inch reduced section approximately 0.500 inch wide. The casting alloys were cast into a tilting slab mold which gave a 1/2-inch thick plate. This plate was cut up into bars 1-inch wide which were sawed down the center edgewise to give two pieces 1/4 inch by 1 inch by 8 inches. The pieces were then heat treated. After heat treating, the pieces were milled on the mold side sufficient to clean up the surface oxidation and then the other side was milled to give a specimen 0.150-inch thick. It was thought that in this manner the soundest metal adjacent to the mold face would be utilized for the test bars and the less sound center section milled away. The specimens were X-rayed before coating and the soundest pieces selected for test. Even with these precautions the cast specimens showed evidence of microporosity into which the coating penetrated. The 220 alloy was not melted in strict accordance with the procedure recommended by the Aluminum Company of America and the properties of the uncoated specimens did not approach the excellent properties attainable with this alloy under ideal conditions.

The tensile tests were conducted on a 50,000 pound capacity Baldwin Southwark machine. It was found necessary to chemically strip the coating off of the grip ends in order to prevent them slipping. Stress-strain curves were plotted with an autographic extensometer system and the 0.2% offset yield strength determined from these curves. The data are given in Tables VII through XV.

It has been shown in a previous section of this report, that the coating grows an amount equal to one-half its thickness. Stated in other words, a thickness of parent metal equal to one-half the coating thickness is consumed in the formation of the coating. If the coating has a strength which is half that of the parent metal, a calculation of yield strength on the basis of original area (which includes half the coating thickness) should give approximately the same strength for all coating thicknesses. As the tables show, the yield strengths calculated on this basis show a continual decrease with increase in coating thickness. This decrease in yield strength is greater for the higher strength alloys and the coating strength is therefore closer to being a fixed value rather than proportional to alloy strength. This is to be expected inasmuch as the primary constituent of all the coatings is the same.

The load capable of being supported by the parent metal remaining after coating was calculated using the average of the yield strengths of the two uncoated specimens as a basis. The load carried by the coating was then estimated by subtracting this value from the actual load supported by the specimen. The load carried by the coating shows a general increase with coating thickness in all cases. Dividing this value by the coating thickness gave a value for the load carried per 0.001 inch of coating. This value shows a general decrease with increase in coating thickness which agrees with the observation that the thicker coatings become more powdery and porous due to the solvent action of the electrolyte. The coating appears to have an average yield strength value of 10,000 - 15,000 p.s.i. The calculation of tensile strength values was not attempted because of the flaking off of the coating in a number of cases soon after the yield strength was passed and the apparent increase in the surface crazing.

The recommended procedure for design calculation of strength would be to use the area of the parent metal remaining after coating which is easily arrived at by subtracting half the coating thickness for each thickness of coating applied to a given dimension.

Compression Tests

The compression tests were conducted on specimens which were 0.500 inch wide by 2-5/8 inches long. The thickness was that of the sheet stock which ranged from 0.032 to 0.081 inch. The cast specimens were machined to 0.150 inch as described for the tensile tests. The specimens were mounted in a Montgomery-Templin compression jig and placed in the Baldwin-Southwark testing machine. The platens of the machine were made parallel by rigidly clamping a spherical mounted upper platen in place after it was run down onto a 2-1/2 inch block with parallel sides resting on the lower platen. Deformation was measured on a dial gage mounted next to the Montgomery-Templin fixture. The results of the tests are tabulated in Tables XVI through XXIII.

The yield strength calculated on the basis of the composite shows a general increase in all cases. This is in contrast to the tensile data where the yield strength calculated on the basis of original area (which only takes into account one-half of the coating thickness) shows a general decrease. This proves that the coating has a higher compression strength than tensile strength. If the yield loads are reduced down to load carried per 0.001 inch, the values are higher than the tensile values. The average compression yield strength of the coating appears to lie in the range of 50,000 - 60,000 p.s.i. as compared to 10,000 - 15,000 p.s.i. tensile yield strength. It is to be understood that these values apply only to the coating as bonded to the base metal.

In the case of coatings on compression members it is safe design practice to use the total area of the composite (coating and metal) and the yield strength of the metal.

Rain Erosion

The resistance of the coatings on the various wrought alloys to erosion by rain when traveling at high velocity was tested in the Cornell Aeronautical Laboratory, Inc. Rain Erosion Tester. In this test the specimens are formed into a contour which simulates the leading edge of an airfoil and are attached to a propeller which is rotated at a speed that causes the midpoint of the specimens to strike a uniform rainfall at 500 m.p.h. Two thicknesses of coating were tested on each wrought alloy. All of the specimens were first given a five minute run in the machine. The appearance of the specimens after this five minute run is shown in Figure 47.

The 24S bare coatings have spalled off badly and the layers referred to previously can be seen in the 0.003-inch coated specimen. The 0.005-inch coated specimens of 75S and XA78S have chipped out about an equal amount which was taken as the end point in the next series of tests. The heavier coatings are evidently more susceptible to damage than the thinner ones.

The specimens which were not damaged as badly as the 0.005-inch coated 75S and XA78S were given additonal runs of five minute increments until damage appeared to be close to the end point when one minute increments were used. These specimens are shown in Figure 48. The 0.003-inch coating on the 24S Alclad showed the best resistance to rain erosion by holding up for a 40-minute period. The other results are tabulated below:

Alloy	Coating Thickness Inches	Time of Exposure Minutes
24S Alclad	0.003	40
61S	0.003	35
75S	0.003	26
61S	0.005	25
XA78S	0.003	25
24S Alclad	0.005	20
75S	0.005	5
XA78S	0.005	5
24S bare	0.003	3 (est.)
24S bare	0.005	1 (est.)

The decrease in rain erosion resistance with increase in thickness is also apparent in these results. The differences in the mode of failure are interesting. The 24S bare alloy appears to spall off in layers while the heavy coatings on 61S, 75S, and XA78S and the 0.003-inch coating on 61S seem to have a failure pattern that is related to the microcrack pattern shown in Figure 5. The 0.003-inch coatings on the 75S and XA78S appear to have been worn through. The 0.005-inch coating on the 24S Alclad shows a spalling type of failure - the notch at the lower end of this specimen was caused by a slip in machining and was discounted.

Effect of Gunfire Penetration

It was thought that the coating may have an embrittling effect on the aluminum alloys when hit by gunfire and lead to crack propagation and general disintegration under this condition. The possibility also existed that general spalling of the coating and local disintegration of the base metal might lead to the production of secondary projectiles which would be undesirable.

Panels of the 24S-T4 and 75S-T6 alloys 0.081-inch thick and measuring 8 inches by 8 inches were coated on one side only with a 0.003-inch thick coating. Uncoated panels of each alloy were used for comparison. The panels were mounted in a rack and fired at with a .30 caliber rifle using standard M-2 ball ammunition which produces an approximate muzzle velocity of 2800 ft./sec. The distance between the muzzle and panels was 70 yards. The panels were mounted at two different angles of incidence to the line of fire, 45 and 90 degrees. Two panels were fired for each angle of incidence; one with the coating toward the muzzle and one with the coating on the far side. Photographs were taken of each plate fired and these are shown in Figure 49. They show that there is no sign of embrittlement or crack propagation due to the coating process. The coating itself does not become detached over wide areas but spalls off only locally around the penetration area. It is felt that the coating would have a negligible effect on the ballistic limit of the alloys.

Coefficient of Expansion

The effect of 0.002-inch and 0.004-inch coatings on the coefficient of expansion was determined for all seven of the aluminum alloys under investigation. Dilatometer curves were also determined on uncoated specimens to obtain comparative data.

All specimens were approximately 5.5 inches by 3/16 inch by 0.081 inch. A temperature range of -40°F to 600°F was covered in two stages. The higher temperature measurements were obtained by placing the specimens between quartz rods in a Vitreosil tube which was heated by a resistance wound tube furnace. The temperature range between -40°F and 78°F was covered by placing the specimen assembly in a steel tube immersed in alcohol which was cooled by the freon coils of a refrigeration unit. Temperatures were measured with a thermocouple attached to the specimen and a potentiometer.

Curves of $\Delta L/L$ metal vs. temperature (°F) were plotted from the values obtained and temperature coefficients determined from these curves for the temperature ranges under consideration. A deviation from linearity in the plots of $\Delta L/L$ metal vs. temperature was observed when approaching room temperature from both directions. This deviation was the result of "slack" in the system since the data were obtained in both cases starting from room temperature. The coefficients of expansion for the ranges on either side of room temperature were obtained by extrapolating the linear portions of the curves. Since similar analysis was applied to all samples any error would be eliminated when the values of the coefficients were compared on a relative basis.

The coefficients of linear expansion for the alloys investigated are tabulated in Table XXIV.

Thermal Shock

Specimens of the five wrought alloys with 0.002-inch and 0.004-inch coating thicknesses were subjected to thermal shock by heating them to 930°F and quenching them in cold water. The heating and quenching were repeated five times. The condition of the coating was determined by visual examination after each quench. The abrasion resistance of the coatings was measured on the Abrasiometer before the tests started, after the first quench and after the fifth quench. The results of these tests are given in Table XXV.

The data show that the coating will not spall off if it should be found necessary to heat treat an aluminum alloy after it has been hard coated; however, the data also show that there is a considerable decrease in the abrasion resistance upon heating the coating. This decrease is relatively greater for the 0.004-inch coating than for the 0.002-inch coatings.

Corrosion Resistance

Test specimens were exposed to three sets of conditions which are liable to lead to metallic corrosion. The two sets of abrasion specimens, one of which was exposed to atmospheric conditions on an outdoor exposure rack on the roof of Cornell Aeronautical Laboratory, Inc. and the other to high relative humidity at 80-90°F, were also good checks on the relative corrodibility of the specimens in these mediums. A third set of specimens was exposed in a salt spray cabinet according to A.S.T.M. Designation B117-49T. The data reported herein were accumulated over a seven-month period. These tests will be continued for an elapsed time of one year and a supplementary report issued at that time. At the end of a 220-day period, the coatings have stood up well when compared with the usual anodized coatings. The failures that have been noted to date are listed in the following paragraphs:

1. Atmospheric Exposure Test Data

At the end of a seven-month exposure to the atmosphere the only failures that occurred were in the 24S bare alloy. These failures took place in the following order:

0.002-inch coating - 180 days

0.003-inch coating - 220 days

0.004-inch coating - 180 days

0.005-inch coating - 220 days

2. Humidity Test Data

The coatings on three of the seven alloys have shown some deterioration under these conditions.

The 24S alloy coating failures occurred as follows:

0.005-inch coating - 60 days

0.004-inch coating - 150 days*

0.003-inch coating - 150 days

0.002-inch coating - 180 days

0.001-inch coating - 180 days

0.0005-inch coating - 150 days

The 24S Alclad coatings showed the following results:

0.005-inch coating - 30 days

0.004-inch coating - 30 days

At the end of 220 days, these two thicknesses are the only ones pitted.

The XA78S coatings held up as follows:

0.0005-inch coating - 120 days

0.001-inch coating - 180 days

The 220 and 356 cast alloys showed pits at the edges at the end of 90 days and show no surface pitting at the end of a 220-day period.

*All of the coatings between 0.005 inch and 0.004 inch showed some evidence of pitting at the end of 120 days but were not considered as failed until the times noted.

3. Salt Spray Test Data

The salt spray test data are summarized in Table XXVI. The 24S bare alloy coating is the only one showing any serious deterioration in this environment.

The corrosion test data serve to emphasize two trends which are apparent in other sections of this report.

1. The 24S bare alloy is not compatible with the hard coating process used (MHC Process).

2. The heavier coatings, over 0.003-inch thickness, are not as desirable as the coatings in the 0.002 - 0.003-inch range.

The coating itself is inert to the base metal and is not likely to lead to galvanic corrosion as in the case of electroplatings of a more cathodic metal. There is a possibility of some difference in behavior due to the difference in the type and concentration of unconverted inclusions in the coating. However, it is felt that the greatest difference in the coatings regarding corrosion behavior is in the soundness of the coating. The 24S bare coatings are rough and blistery in appearance. This probably accounts for the early breakdown of these coatings. The 24S Alclad with heavier coatings was shown to form blisters in some cases. This could possibly explain the failures in the heavier coatings in this alloy. The maze of cracks that form in the coating due to differences in expansion coefficients undoubtedly act as capillary channels down to the base metal in the presence of liquid corrosion media which are even more accessible than the pores in the oxide coating itself.

Regardless of these factors, the coating adds to the corrosion resistance of aluminum alloys under conditions usually encountered in aircraft service.

DISCUSSION

A discussion of the results has been included in the individual sections covering the various tests. The data have been analyzed from a comparative standpoint regarding differences existing between the various alloys tested and various thicknesses of coating. Without a specific application in mind a detailed analysis of the test data in which the interrelationship of the various results would be considered is not possible. This must be left to the engineer or designer who has a well defined application and knows the results expected.

In general, the hard oxide coating process is undoubtedly the solution for many problems demanding a light or corrosion resistant (atmospheric) material with a hard, wear resistant surface not subjected to point loading. The decrease in corrosion resistance upon exposure to high humidity and atmospheric conditions could probably be overcome by proper post-treatment of the coated surface. The effect of the coating on the fatigue strength raises a serious objection to its use in applications subject to cyclic stresses. It is doubtful that this effect can be readily overcome. The coating does not seriously affect any of the other mechanical properties. However, the minor effects on these properties may be a distinct advantage in some applications or a disadvantage in others.

CONCLUSIONS

The direct conclusions to be drawn from the results of the individual types of tests have also been brought out in the individual report sections on a comparative basis. The full value of the data cannot be appreciated until they are analyzed with respect to a given application. The following general conclusions may be drawn:

1. The hard oxide coatings provide a means of extending the use of aluminum and its alloys into fields hitherto restricted to them because of their soft surface.

2. The increase in wear resistance is the most outstanding property conferred on aluminum alloys by the hard coatings.

3. The decrease in endurance strength brought about by the hard coatings is the greatest objection to their use in applications where high cyclic stresses are likely to be encountered.

4. The other properties of the coatings such as, dielectric strength, color, corrosion resistance, etc. may determine their choice for specific applications.

5. A careful analysis of all of the properties of the coating and the effect of the coating on the properties of the base metal should be made before it is selected for other than experimental applications.

6. The hard coating process will undoubtedly lead to the development of new products which will be dependent upon the unique combinations of properties available only through its use.

BIBLIOGRAPHY

1. British Patent 223,994, November 3, 1924, G. D. Bengough and John M. Stuart.

2. U. S. Patent 1,771,910, July 29, 1930, D. Bengough and J. Stuart (England).

3. Hogaboon, George B., "Anodizing Aluminum - A Patent History and Digest", Metal Finishing, Vol. 43, No. 12, December, 1945, pp. 500-503.

4. U. S. Patent Application Serial No. 157640, Martin Hard Coat (MHC) Process.

5. "New Coated Aluminum is Wear Resistant", Aviation Week, Vol. 52, No. 26, June 26, 1950, p. 26.

6. "MHC" Light Metal Age, August, 1950, pp. 18, 20.

7. "New Hard Coating Gains Wear Applications for Aluminum", Materials and Methods, Vol. 32, August, 1950, pp. 62-64.

8. "New Finish Gives Aluminum Good Wear Resistance", Iron Age, Vol. 166, No. 8, August 24, 1950, pp. 73-75.

9. "New Hard Finish for Aluminum Alloys", Metal Finishing, November, 1950, pp. 51-63, 74.

10. "Hard Surfacing Light Alloy by Anodizing", Light Metals, February, 1952, pp. 46-48.

11. "A Study of the Rain Erosion of Plastic Materials", Monthly Progress Report for December, 1951, Cornell Aeronautical Laboratory, Inc. for Wright Air Development Center, Wright-Patterson Air Force Base, Contract No. AF 33(038)-514.

12. Keller, F., "Anodic Coatings Seen Through the Microscope", Proceedings A.S.T.M., Vol. 40, pp. 948-958.

13. Edwards, Junius D., "Thickness of Anodic Coatings on Aluminum", Proceedings A.S.T.M., Vol. 40, 1940, pp. 959-966.

14. Anderson, Scott, "Mechanism of Electrolytic Oxidation of Aluminum", Journal of Applied Physics, Vol. 15, June 1944, pp. 477-480.

15. Edwards, J. and Keller, F., "The Structure of Anodic Oxide Coatings", Transactions A.I.M.E., Institute of Metals Division, Vol. 156, 1944, pp. 288-300.

16. Frary, Francis C., "The Complexities of Aluminum Oxide", Light Metal Age, February, 1946, pp. 33-42.

17. Keller, F. and Edwards, J., "Composition and Properties of the Natural Oxide Films on Aluminum", Metal Progress, Vol. 54, 1948, pp. 195-200.

18. Arlt, H.G., "The Abrasion Resistance of Anodically Oxidized Coatings on Aluminum", Proceedings A.S.T.M., Vol. 40, 1940, pp. 967-977.

19. "Standard Method of Test for Dielectric Strength of Anodically Coated Aluminum", A.S.T.M. Standards, Part I-B, 1946, pp. 185-186.

20. Compton, K.G. and Mendizza, A., "Electrical Breakdown of Anodically Oxidized Coatings on Aluminum: A Means of Checking Anodized Finishes", Proceedings A.S.T.M., Vol. 40, 1940, pp. 978-987.

21. Phillips, S.H., "Heat Testing of Aluminum Coatings", Light Metal Age, May, 1947, p. 26.

ACKNOWLEDGMENT

The assistance of Associate Professor M. Burton of the Metallurgy Department of Cornell University in the X-ray diffraction studies of the coating and of Mr. J. McCarthy of the Department of Metallurgical Engineering of Rensselaer Polytechnic Institute in the determination of the dilatometer curves, is hereby acknowledged.

We also wish to express our appreciation to Mr. R. Vanden Berg of the Aluminum Company of America's Process Development Laboratory, and Mr. C. F. Burrows of Metal Finishers, Inc. for their cooperation and assistance in setting up the hard coating process.

TABLE I

BEND TESTS

61S-T6 0.051-INCH THICK

Radius Required for 90° Bend of Base Metal 1/16 - 1/8 Inch

Coating Thickness Inches	Compression Side Bend Radius - Inches	Tension Side Bend Radius - Inches
0.0005	7/16 flaking*	1/16 base metal failure
0.0005	3/8 "	1/16 " " "
0.001	7/16 flaking	3/32 base metal failure
0.001	1/2 "	3/32 " " "
0.002	3/4 flaking, 1 inch spalling**	3/16 base metal failure
0.002	3/8 " 1/2 inch "	3/16 " " "
0.003	1/2 spalling	1/8 base metal failure
0.003	1/2 "	***1/2 edge flaking 1/8 B.M.
0.004	5/8 spalling	3/32 base metal failure
0.004	1/2 "	3/32 " " "
0.005	5/8 spalling	3/32 base metal failure
0.005	5/8 "	3/32 " " "

Note: *The term "flaking" is used to indicate a localized pitting of the outer layers of the coating of approximately 1/16 inch diameter near the center of the bent section.

**The term "spalling" is used to indicate a sudden disengagement of the full thickness of the coating, usually over an area over 1/16 inch diameter.

***Edge spalling and edge flaking on the tension side always precede failure of the base metal at about twice the bend radius at failure. The center of the bent section is visibly sound until base metal failure occurs.

TABLE II

BEND TESTS

XA78S-T6 0.064 INCH THICK

Radius Required for 90° Bend of Base Metal 3/16 - 5/16 Inch

Coating Thickness Inches	Compression Side Bend Radius - Inches	Tension Side Bend Radius - Inches
0.0005	5/16 spalling	1/4 base metal failure
0.0005	1/4 "	1/4 " " "
0.001	5/16 spalling	1/4 base metal failure
0.001	5/16 "	5/16 " " "
0.002	7/8 base metal failure	7/8 base metal failure
0.002	5/16 spalling	1/4 " " "
0.003	1/2 spalling	1/2 base metal failure
0.003	7/16 "	3/8 " " "
0.004	5/8 spalling	3/4 spalling at edges
0.004	7/16 spalling	3/4 " " " "
0.005	5/8 spalling	5/8 spalling at edges
0.005	1/2 "	5/8 " " "

TABLE III

BEND TESTS

24S-T3 BARE 0.051 INCH THICK

Radius Required for 90° Bend of Base Metal 1/8 - 1/4 Inch

Coating Thickness Inches	Compression Side Bend Radius - Inches	Tension Side Bend Radius - Inches
0.0005	5/16 flaking	3/32 base metal failure
0.0005	1/2 "	3/32 " " "
0.001	1 spalling	3/16 flaking at edges
0.001	1-1/2 spalling	3/16 " " "
0.002	1-1/4 spalling	3/8 spalling at edges
0.002	1-1/4 "	3/16 base metal failure
0.003	1-1/4 spalling	1/2 spalling at edges 1/8 B.M.
0.003	1-1/2 "	3/4 " " " 3/32 B.M.
0.004	1-1/2 spalling	1 spalling at edges 3/32 B.M.
0.004	2 spalling	1 " " " 3/32 B.M.
0.005	1-1/2 spalling	1 spalling at edges 3/32 B.M.
0.005	1-1/2 "	3/4 " " " 3/32 B.M.

TABLE IV

BEND TESTS

24S-T4 ALCLAD 0.051 INCH THICK

Radius Required for 90° Bend of Base Metal 1/8 - 1/4 Inch

Coating Thickness Inches	Compression Side Bend Radius - Inches	Tension Side Bend Radius - Inches
0.0005	1/2 flaking	3/32 base metal failure
0.0005	3/4 "	3/32 " " "
0.001	7/8 flaking	1/8 base metal failure
0.001	1 "	3/32 " " "
0.002	3/4 spalling	3/8 base metal failure
0.002	5/8 "	1/4 " " "
0.003	5/8 spalling	3/16 base metal failure
0.003	1/4 "	3/16 " " "
0.004	5/8 spalling	3/32 base metal failure
0.004	1/2 "	3/32 " " "
0.005	5/8 spalling	3/32 base metal failure
0.005	5/8 "	3/32 " " "

TABLE V

BEND TESTS

75S-T6 0.051 INCH THICK

Radius Required for 90° Bend of Base Metal 3/16 - 5/16 Inch

Coating Thickness Inches	Compression Side Bend Radius - Inches	Tension Side Bend Radius - Inches
0.0005	1/4 spalling	3/16 base metal failure
0.0005	3/16 "	1/8 " " "
0.001	1/4 spalling	3/16 base metal failure
0.001	3/8 "	3/16 " " "
0.002	3/8 spalling	3/16 base metal failure
0.002	3/8 "	3/16 " " "
0.003	3/4 spalling	1/2 spalled edges 3/16 B.M.
0.003	1/2 "	1/2 " " 1/4 B.M.
0.004	7/16 spalling	7/16 spalled edges 3/16 B.M.
0.004	1/2 "	1/2 " " 5/16 B.M.
0.005	1/2 spalling	5/16 " " 1/4 B.M.
0.005	3/4 "	3/8 " " 1/4 B.M.

TABLE VI

FLAME TESTS

Note: All specimens 4 inches by 4 inches by thickness as given in column 1.

Alloy and Sheet Thickness	Coating Thickness - Inches							
	0.000	0.000	0.001	0.001	0.003	0.003	0.005	0.005
	Time to Failure - Minutes							
61S 0.051 Inch	0.52	0.49	0.60	0.52	0.74	0.86	0.87	0.85
XA78S 0.064 Inch	0.63	0.60	0.83	0.87	1.09	1.02	0.94	1.05
24S 0.051 Inch	0.50	0.56	0.70	0.71	0.77	0.76	0.97	1.02
24S Alclad 0.051 Inch	0.55	0.55	0.64	0.79	0.78	0.82	1.10	1.02
75S 0.051 Inch	0.48	0.49	0.66	0.68	0.90	0.73	0.98	0.94
356 Thickness	2.55 0.200 Inch	-	3.08 0.175 Inch	-	4.06 0.187 Inch	-	4.81 0.204 Inch	-
220 Thickness	2.25 0.197 Inch	-	3.29 0.208 Inch	-	5.20 0.206 Inch	-	3.10 0.190 Inch	-

TABLE VII

TENSILE TEST DATA 61S-T6 ALLOY - 0.032 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq.In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 Ins.
0.000	0.0154	-	658	42,700	-	Based on 42,750 psi. Y.S.	-	-	734	47,700	-	12.0
0.000	0.0161	-	690	42,800	-	-	-	-	774	48,100	-	14.0
0.0005	0.0163	0.0160	700	43,000	43,800	684	16	16	800	49,100	50,000	12.5
0.0005	0.0157	0.0155	673	41,300	43,400	664	9	9	764	49,200	49,300	12.5
0.001	0.0156	0.0151	667	42,700	44,200	645	22	11	761	48,800	50,400	11.5
0.001	0.0162	0.0157	682	42,100	43,400	671	11	5.5	790	48,700	50,300	9.0
0.002	0.0162	0.0152	660	41,000	43,400	650	10	2.5	762	47,100	50,200	9.5
0.002	0.0162	0.0151	664	41,200	44,000	645	19	5	762	47,100	50,500	8.5
0.003	0.0163	0.0147	642	39,400	43,700	628	14	2.5	736	45,400	50,100	8.0
0.003	0.0161	0.0145	-	-	-	620	-	-	732	44,900	50,500	8.0*
0.004	0.0165	0.0143	638	38,700	44,600	611	27	3.5	726	44,000	50,700	8.0
0.004	0.0165	0.0143	638	38,700	44,600	611	27	3.5	725	43,800	50,700	8.5
0.005	0.0153	0.0127	622	40,600	49,000	543	79	7.9	690	45,100	54,300	5.5
0.005	0.0162	0.0135	571	35,200	42,300	577	-6	-	643	39,700	47,600	7.0**

* No stress-strain record.

** Coating flaked off.

TABLE VIII

TENSILE TEST DATA 61S-T6 ALLOY - 0.050 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq.In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 Ins.
0.000	0.0255	-	1070	42,000	-	Based on 41,850 psi. Y.P.	-	-	1170	45,800	-	12.5
0.000	0.0259	-	1080	41,700	-	-	-	-	1170	45,200	-	12.0
0.0005	0.0259	0.0256	1070	41,300	41,800	1070	0	0	1190	46,000	46,500	10.0
0.0005	0.0260	0.0257	1080	41,500	42,100	1075	5	5	1190	45,800	46,300	11.5
0.001	0.0258	0.0252	1060	41,200	42,100	1054	6	3	1180	45,800	46,800	10.0
0.001	0.0260	0.0254	1070	40,800	42,200	1062	8	4	1190	45,800	46,800	9.0
0.002	0.0256	0.0246	1083	42,300	44,100	1030	53	13	1205	47,100	49,000	8.5
0.002	0.0258	0.0245	1070	41,500	43,700	1025	45	11	1194	48,200	48,800	9.0
0.003	0.0259	0.0242	1072	41,400	44,300	1012	60	10	1186	45,800	49,000	7.5
0.003	0.0256	0.0239	1053	41,200	44,100	1000	53	9	1171	45,800	49,000	7.5
0.004	0.0259	0.0235	1047	40,400	44,600	985	62	8	1161	44,900	49,400	8.5
0.004	0.0258	0.0235	1046	40,500	44,600	985	61	7.5	1161	45,100	49,400	6.0
0.005	0.0255	0.0227	1008	39,400	44,400	950	58	5.8	1110	43,500	48,800	7.5
0.005	0.0256	0.0226	1008	39,300	44,600	946	62	6.2	1112	43,700	49,200	7.0

TABLE XI

TENSILE TEST DATA 24S-T3 - 0.032 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq. In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 In.
0.000	0.0164	-	830	50,600	-	Based on 50,450 psi. Y.S.	-	-	1110	67,700	-	18.0
0.000	0.0163	-	820	50,300	-	-	-	-	1090	66,800	-	16.0
0.0005	0.0164	0.0162	820	50,000	50,600	817	3	3	1090	66,500	67,300	17.5
0.0005	0.0166	0.0163	810	48,800	49,700	822	-12	-12	1080	65,100	66,300	15.0
0.001	0.0164	0.0163	825	50,200	50,600	822	3	1.5	1102	67,200	67,700	15.0
0.001	0.0164	0.0163	827	50,400	50,700	822	5	2.5	1091	66,600	66,800	15.5**
0.002	0.0161	0.0150	800	49,700	53,300	756	44	11	1061	66,000	70,700	14.0**
0.002	0.0163	0.0152	807	49,500	53,100	766	41	10	1057	64,800	69,500	15.0 (1)
0.003	0.0165	0.0148	790	47,800	53,400	747	43	7	1035	62,700	70,000	- * (2)
0.003	0.0164	0.0148	787	48,000	53,200	747	40	7	1050	64,100	71,000	11 (3)
0.004	0.0165	0.0148	767	46,500	51,800	747	20	2.5	982	59,600	66,400	- * (4)
0.004	0.0165	0.0144	737	44,500	51,200	726	13	1.5	990	60,000	68,700	- * (4)
0.005	0.0166	0.0139	737	44,400	53,000	701	36	3.5	972	58,600	69,800	- * (4)
0.005	0.0167	0.0139	720	43,200	51,800	701	19	2	973	58,200	70,000	- * (4)

* Gage marks were lost when coating flaked off.
** Slight flaking.
(1) Started flaking at 1035 pounds.
(2) Started flaking at 995 pounds.
(3) Started flaking at 1010 pounds.
(4) Flaked off entirely.

TABLE XII

TENSILE TEST DATA 24S-T4 ALCLAD - 0.032 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq. In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 In.
0.000	0.0167	-	830	49,700	-	Based on 49,400 psi. Y.S.	-	-	1070	64,200	-	17.5
0.000	0.0167	-	820	49,100	-	-	-	-	1106	66,200	-	16.5
0.0005	0.0169	0.0166	845	50,000	50,800	820	25	25	1104	65,400	66,600	16.0
0.0005	0.0166	0.0163	843	50,800	51,700	805	38	38	1108	66,700	68,000	14.0
0.001	0.0165	0.0160	832	50,400	52,000	790	42	21	1107	67,000	69,200	14.0
0.001	0.0166	0.0161	827	49,800	51,400	795	32	16	1110	66,900	69,000	12.5
0.002	0.0170	0.0159	827	48,700	52,000	785	42	11.5	1117	65,600	70,200	14.0
0.002	0.0168	0.0157	832	49,700	53,000	775	57	14	1106	65,800	70,400	13.0
0.003	0.0168	0.0152	833	49,600	54,800	750	83	14	1077	64,000	70,800	11.5
0.003	0.0166	0.0149	832	50,100	55,800	735	87	14	1075	64,800	72,200	12.0
0.004	0.0166	0.0144	-	-	-	-	-	-	1025	61,800	71,200	- * (1)
0.004	0.0167	0.0146	788	47,200	54,000	720	68	8	1026	61,400	70,300	- * (1)
0.005	0.0169	0.0141	785	46,400	55,700	696	89	9	982	58,200	69,700	- * (1)
0.005	0.0169	0.0142	787	46,600	55,400	701	86	8.5	971	57,500	68,300	- * (1)

* Gage marks were lost when coating flaked off.
(1) No stress-strain record. Coating flaked off entirely.

TABLE XIII

TENSILE TEST DATA 75S-T6 - 0.033 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq. In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 In.
0.000	0.0165	-	1210	73,300	-	Based on 73,400 psi. Y.S.	-	-	1320	80,000	-	8.5
0.000	0.0162	-	1190	73,500	-	-	-	-	1300	80,300	-	10.0
0.0005	0.0160	0.0158	1140	71,200	72,200	1160	-20	-20	1290	80,600	81,700	7.5
0.0005	0.0163	0.0160	1160	70,700	72,700	1175	-15	-15	1300	79,800	81,300	8.5
0.001	0.0163	0.0157	1160	71,200	73,800	1152	8	4	1300	79,800	82,800	7.5
0.001	0.0162	0.0157	1160	71,600	73,800	1152	8	4	1310	81,000	83,400	8.0
0.002	0.0162	0.0151	1130	69,800	74,800	1110	20	5	1270	78,400	84,200	7.0
0.002	0.0163	0.0153	1140	70,000	74,500	1123	17	4	1300	79,800	85,000	7.0
0.003	0.0163	0.0147	1120	68,900	76,200	1080	40	7	1270	78,000	86,400	7.0
0.003	0.0158	0.0143	1120	71,000	78,400	1050	70	12	1240	78,500	86,800	7.0
0.004	0.0163	0.0142	1100	67,500	77,500	1042	58	7	1230	75,500	86,700	5.5*
0.004	0.0162	0.0141	1100	67,900	78,100	1036	64	8	1240	76,600	88,000	5.5*
0.005	0.0162	0.0136	1050	64,900	77,300	1000	50	5	1180	72,900	86,800	6.5*
0.005	0.0161	0.0135	1050	65,200	77,800	991	59	6	1160	72,100	86,000	6.0*

* Coating started to peel off.

TABLE XIV

TENSILE TEST DATA 356-T6 - 0.150 INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq. In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 In.
0.000	0.0779	-	1250	16,050	-	Based on 16,500 psi. Y.S.	-	-	1930	24,750	-	3.0
0.000	0.0768		1300	16,930	-	-	-	-	2000	26,050	-	4.5
0.001	0.0762	0.0762	1310	17,200	17,360	1258	52	26	2260	29,700	29,950	6.5
0.001	0.0770	0.0770	1280	16,600	16,750	1270	10	5	2310	30,000	30,200	6.5
0.003	0.0775	0.0775	1280	16,500	16,970	1280	0	0	2040	26,350	27,050	4.0
0.003	0.0768	0.0768	1330	17,300	17,770	1268	62	10	2430	31,700	32,500	6.5
0.005	0.0775	0.0775	1350	17,400	18,230	1280	70	7	2420	31,200	32,700	5.5
0.005	0.0775	0.0775	1290	16,700	17,400	1280	10	1	2100	27,100	28,300	3.0

Note: The metal had an open structure and the oxide coating penetrated into the pores further reducing strength and ductility.

TABLE XV

TENSILE TEST DATA 220-T4* - 0.051-INCH THICK

Coating Thickness In.	Area of Original Parent Metal Sq. In.	Area of P.M. Remaining After Coating Sq. In.	Load at Y.S. 0.2% Offset Lbs.	Y.S. Based on Original Area Psi.	Y.S. Based on P.M. Area After Coating Psi.	Load Carried by P.M. Lbs.	Load Carried by Coating Lbs.	Load Carried per 0.001 In. Coating	Load Ultimate Lbs.	U.T.S. Based on Original Area Psi.	U.T.S. Based on P.M. Area After Coating Psi.	% Elong. In 2 In.
0.000	0.0806	-	1920	23,850	-	Based on 23,100 psi. Y.S.	-	-	2500	31,050	-	O.G.L.
0.000	0.0811	-	1810	22,300	-	-	-	-	2260	27,900	-	2.5
0.001	0.0782	0.0782	1770	22,600	22,850	1810	-40	-40	2340	29,900	30,200	3.5
0.001	0.0802	0.0802	1850	23,100	23,250	1850	0	0	2420	30,200	30,400	2.0
0.003	0.0796	0.0796	1880	23,600	24,250	1840	40	7	2610	32,800	33,650	3.5
0.003	0.0732	0.0732	1700	23,200	23,850	1690	10	1.5	2260	30,900	31,700	2.0
0.005	0.0820	0.0820	1670	20,400	21,300	1895	-225	-	1900	23,200	24,200	1.0
0.005	0.0782	0.0782	1640	21,000	21,900	1810	-170	-	2000	25,600	26,700	1.0

* The 220 casting alloy was not melted in strict accordance with the procedure patented by the Aluminum Company of America and the resulting properties did not approach the values usually attained by this alloy.

Note: The metal had an open structure and the oxide coating penetrated into the pores further reducing strength and ductility.

TABLE XVI

COMPRESSION TEST DATA 61S-T6 - 0.050 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0249 Sq.In.	- Sq.In.	1050 Lbs.	42,200 Psi.	Based on 41,950 psi. Y.S.	-	-
0.000	0.0247	-	1050	41,700	-	-	-
0.0005	0.0250	0.0247	1080	43,200	1035 Lbs.	45 Lbs.	90 Lbs.
0.0005	0.0250	0.0247	1070	42,800	1035	35	70
0.001	0.0252	0.0243	1100	43,700	1019	81	81
0.001	0.0252	0.0243	1120	44,500	1019	101	101
0.002	0.0259	0.0248	1120	45,200	1040	80	40
0.002	0.0259	0.0248	1170	45,200	1040	130	65
0.003	0.0265	0.0247	1200	45,300	1035	165	55
0.003	0.0265	0.0247	1200	45,300	1035	165	55
0.004	0.0273	0.0251	1240	45,400	1050	190	47
0.004	0.0274	0.0251	1250	45,600	1050	200	50
0.005	0.0280	0.0252	1250	44,700	1050	200	40
0.005	0.0280	0.0252	1270	45,400	1050	220	44

TABLE XVII

COMPRESSION TEST DATA 61S-T6 - 0.032 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S..	Load Carried by P.M..	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0157 Sq.In.	- Sq.In..	690 Lbs.	43,900 Psi.	Based on 43,300 psi. Y.S.	-	-
0.000	0.0157	-	670	42,700	-	-	-
0.0005	0.0160	0.0158	700	43,800	684 Lbs.	16 Lbs.	32 Lbs.
0.0005	0.0160	0.0158	680	42,500	684	-4	-8
0.001	0.0162	0.0156	730	45,100	675	55	55
0.001	0.0162	0.0156	710	43,800	675	35	35
0.002	0.0168	0.0157	790	47,000	680	110	55
0.002	0.0168	0.0157	760	45,200	680	80	40
0.003	0.0173	0.0157	820	47,400	680	140	47
0.003	0.0173	0.0157	810	46,800	680	130	43
0.004	0.0179	0.0158	890	49,700	684	206	51
0.004	0.0179	0.0158	870	48,600	684	186	47
0.005	0.0183	0.0156	880	48,100	675	205	41
0.005	0.0184	0.0156	890	48,400	675	215	43

TABLE XVIII

COMPRESSION TEST DATA XA78S-T6-0.032 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0323 Sq.In.	- Sq.In.	2600 Lbs.	80,500 Psi.	Based on 81,150 psi. Y.S.	-	-
0.000	0.0323	-	2640	81,800	-	-	-
0.0005	0.0324	0.0322	2690	83,100	2620 Lbs.	70 Lbs.	140 Lbs.
0.0005	0.0324	0.0322	2690	83,100	2620	70	140
0.001	0.0326	0.0320	2720	83,500	2600	120	120
0.001	0.0326	0.0320	2720	83,500	2600	120	120
0.002	0.0329	0.0319	2800	85,100	2590	210	105
0.002	0.0329	0.0319	2750	83,600	2590	160	80
0.003	0.0334	0.0316	2780	83,200	2560	220	73
0.003	0.0334	0.0316	2760	82,600	2560	200	67
0.004	0.0335	0.0316	2750	82,000	2560	190	47
0.004	0.0335	0.0316	2760	82,400	2560	200	50
0.005	0.0341	0.0316	2760	80,900	2560	200	40
0.005	0.0341	0.0316	2750	80,800	2560	190	38

TABLE XIX

COMPRESSION TEST DATA 24S-T3 - 0.051 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0254 Sq. In.	- Sq.In.	1150 Lbs.	45,300 Psi.	Based on 45,500 psi. Y.S.	-	-
0.000	0.0254	-	1160	45,700	-	-	-
0.0005	0.0254	0.0252	1120	44,100	1145 Lbs.	-25 Lbs.	-50 Lbs.
0.0005	0.0254	0.0252	1150	45,300	1145	5	10
0.001	0.0259	0.0253	1180	45,600	1150	30	30
0.001	0.0258	0.0253	1170	45,400	1150	20	30
0.002	0.0264	0.0252	1220	46,200	1145	75	37
0.002	0.0264	0.0252	1200	45,500	1145	55	27
0.003	0.0270	0.0254	1200	44,400	1155	45	15
0.003	0.0270	0.0254	1250	46,300	1155	95	32
0.004	0.0277	0.0254	1230	44,400	1155	75	14
0.004	0.0277	0.0254	1270	45,800	1155	115	29
0.005	0.0283	0.0255	1270	44,900	1160	110	22
0.005	0.0282	0.0255	1170	41,500	1160	110	22

TABLE XX

COMPRESSION TEST DATA 24S ALCLAD - 0.052 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0259 Sq.In.	- Sq.In.	1100 Lbs.	42,500 Psi.	Based on 42,650 psi. Y.S.	-	-
0.000	0.0259	-	1110	42,800	-	-	-
0.0005	0.0265	0.0262	1150	43,400	1115 Lbs.	35 Lbs.	70 Lbs.
0.0005	0.0265	0.0262	1170	44,200	1115	55	110
0.001	0.0264	0.0259	1170	44,300	1105	65	65
0.001	0.0264	0.0259	1160	43,900	1105	55	55
0.002	0.0272	0.0261	1270	46,700	1110	160	80
0.002	0.0272	0.0261	1260	46,300	1110	150	75
0.003	0.0282	0.0266	1350	47,900	1130	220	73
0.003	0.0282	0.0266	1360	48,200	1130	230	77
0.004	0.0284	0.0262	1330	48,800	1115	215	53
0.004	0.0284	0.0262	1390	48,900	1115	275	69
0.005	0.0291	0.0263	1410	48,500	1120	290	58
0.005	0.0291	0.0263	1410	48,500	1120	290	58

TABLE XXI

COMPRESSION TEST DATA 75S-T6 - 0.051 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0253 Sq.In.	- Sq.In.	1810 Lbs.	71,500 Psi.	Based on 71,500 psi. Y.S.	-	-
0.000	0.0253	-	1810	71,500	-	-	-
0.0005	0.0252	0.0249	1810	71,800	1780 Lbs.	30 Lbs.	60 Lbs.
0.0005	0.0252	0.0249	1790	71,100	1780	10	20
0.001	0.0256	0.0250	1790	69,900	1788	2	2
0.001	0.0256	0.0250	1780	69,600	1788	-8	-8
0.002	0.0261	0.0252	1910	73,200	1800	110	55
0.002	0.0261	0.0252	1910	73,200	1800	110	55
0.003	0.0257	0.0250	1950	75,900	1788	162	54
0.003	0.0257	0.0250	1930	75,100	1788	142	47
0.004	0.0268	0.0246	1950	72,800	1760	190	47
0.004	0.0268	0.0246	1930	72,000	1760	170	42
0.005	0.0272	0.0244	1980	72,800	1745	235	47
0.005	0.0272	0.0244	1970	72,500	1745	225	45

TABLE XXII

COMPRESSION TEST DATA 356-T6 - 0.150 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0758 Sq.In.	- Sq.In.	1710 Lbs.	22,300 Psi.	Based on 22,450 psi. Y.S.	-	-
0.000	0.0758	-	1760	22,600	-	-	-
0.001	0.0758	0.0752	1760	22,400	1690 Lbs.	70 Lbs.	- Lbs.
0.001	0.0758	0.0752	1540	20,000	1690	-150	-
0.003	0.0783	0.0754	1440	19,000	1690	-250	-
0.003	0.0771	0.0752	1390	18,300	1690	-300	-
0.005	0.0768	0.736	1350	17,800	1652	-302	-
0.005	0.0779	0.750	1430	18,900	1682	-252	-

Note: The metal had an open structure and the oxide coating penetrated into the pores and the results are not felt to be applicable to sound metal.

TABLE XXIII

COMPRESSION TEST DATA 220-T4 0.150 INCH THICK

Coating Thickness	Area Composite	Area Parent Metal	Load Yield	Composite Y.S.	Load Carried by P.M.	Load Carried by Coating	Load Carried Per 0.001 Inch Coating
0.000 In.	0.0763 Sq.In.	- Sq.In.	2150 Lbs.	28,200 Psi.	Based on 27,100 psi. Y.S.	-	-
0.000	0.0763	-	1980	26,000	-	-	-
0.001	0.0768	0.0762	1770	23,200	2060 Lbs.	-290 Lbs.	- Lbs.
0.001	0.0772	0.0766	1850	24,000	2070	-220	-
0.003	0.0783	0.0764	2330	29,800	2070	-40	-
0.003	0.0783	0.0764	2300	29,400	2070	-70	-
0.005	0.0758	0.0727	1980	26,200	1970	10	-
0.005	0.0758	0.0727	2010	26,500	1970	40	

Note: The metal had an open structure and the oxide coating penetrated into the pores and the results are not felt to be applicable to sound metal.

TABLE XXIV

COEFFICIENTS OF EXPANSION

Alloy	Coating Thickness Inches	(-40)-68°F	68-212°F	68-392°F	68-572°F
61S	0.00	*9.35	10.4	12.7	13.75
61S	0.002	9.5	12.6	13.4	13.6
61S	0.0035	10.35	11.9	13.05	13.3
XA78S	0.00	9.86	12.9	13.9	13.75
XA78S	0.002	9.6	12.45	13.6	13.35
XA78S	0.004	9.85	12.05	13.3	13.5
24S	0.00	10.1	13.0	13.5	14.6
24S	0.002	9.6	11.6	12.8	13.75
24S	0.004	9.8	11.0	12.7	13.8
24S Alclad	0.00	9.85	12.1	13.2	14.1
24S Alclad	0.002	9.35	12.65	13.5	14.1
24S Alclad	0.004	9.55	11.85	12.4	13.4
75S	0.00	9.5	11.1	13.6	13.6
75S	0.002	9.8	13.6	14.0	13.9
75S	0.004	10.1	12.4	13.8	13.65
356	0.00	9.4	11.25	12.55	13.7
356	0.002	9.0	10.8	12.85	13.7
356	0.004	9.5	11.6	12.1	13.4
220	0.00	10.1	13.65	14.1	14.45
220	0.002	10.7	13.6	13.9	14.3
220	0.004	10.35	12.6	13.7	14.3

*Multiply all values by 10^{-6}

TABLE XXV

THERMAL SHOCK TESTS

XA78S	-	0.004-inch coating spalled off slightly after 4th shock.
24S	-	0.004-inch coating spalled off slightly after 4th shock.
75S	-	0.004-inch coating spalled off slightly after 4th shock.

ABRASION TEST DATA

Alloy	Coating Thickness Inches	As-Coated Abrasion Resistance Grams of Abrasive	After 1st Quench Abrasion Resistance Grams of Abrasive	After 5th Quench Abrasion Resistance Grams of Abrasive
61S	0.002	358	299	274
61S	0.0035	743	550	554
XA78S	0.0002	259	294	269
XA78S	0.0004	551	214*	280
24S	0.002	191	161	184
24S	0.004	231	191	74*
24S Alclad	0.002	522	336	334
24S Alclad	0.004	1071	639	500
75S	0.002	451	322	432
75S	0.004	679	334*	304*

*Coating flaked off during abrasion test.

TABLE XXVI

SALT SPRAY TEST DATA

	Days to Failure					
Alloy	0.0005 Inch Thickness	0.001 Inch Thickness	0.002 Inch Thickness	0.003 Inch Thickness	0.004 Inch Thickness	0.005 Inch Thickness
61S	220	*	*	*	*	*
XA78S	*	*	*	*	*	*
24S	60	90	90	150	180	150
24S Alclad	60	90	*	*	*	*
75S	220	*	*	*	*	*
356	**	*	**	*	**	*
220	**	180	**	220	**	*

*Specimen has not failed in 220 days.

**The two casting alloys, 220 and 356 were tested with only 0.00, 0.003, and 0.005-inch coatings.

GRAPH COMPARING WEAR RESISTANCE OF MHC HARD COATING WITH THAT OF VARIOUS OTHER MATERIALS & COATINGS(7)

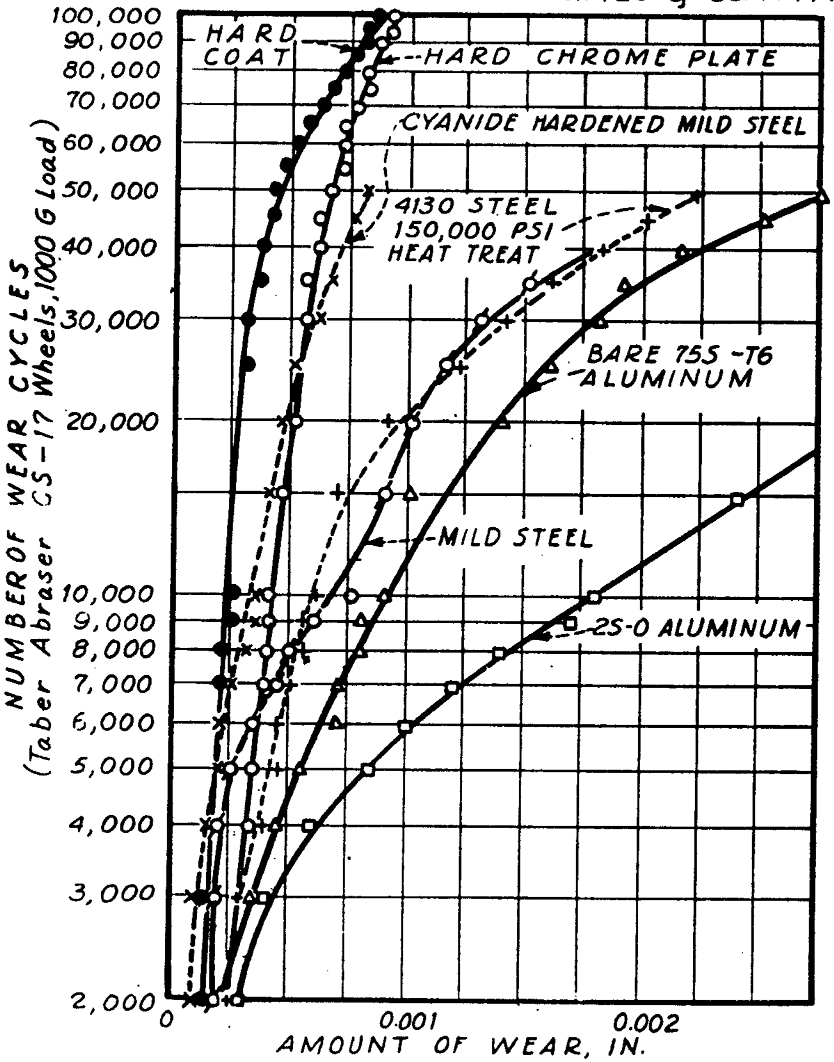


Fig. 1

S-N CURVE ILLUSTRATING MARKED DROP IN ENDURANCE LIMIT OF HARD-COATED ALUMINUM(7)

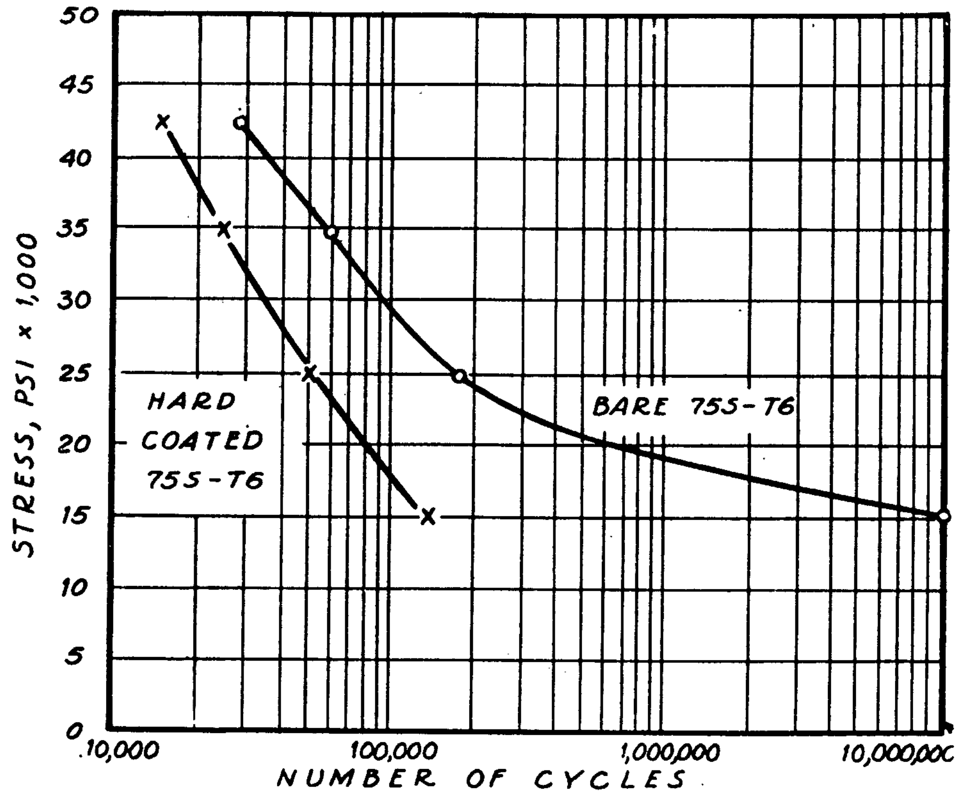


Fig. 2

TIME VS. THICKNESS OF COATING

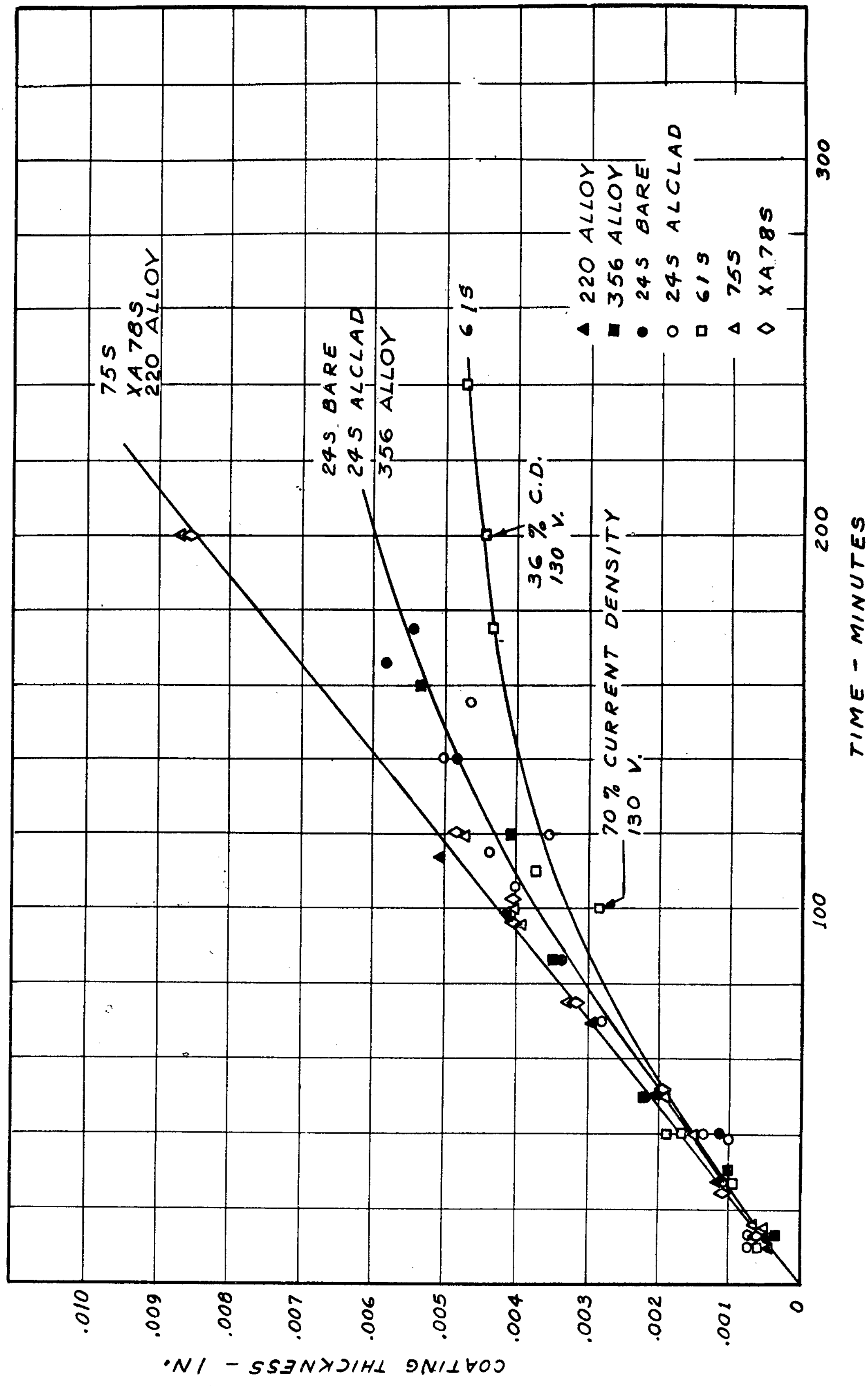


Fig. 3

GROWTH DURING COATING

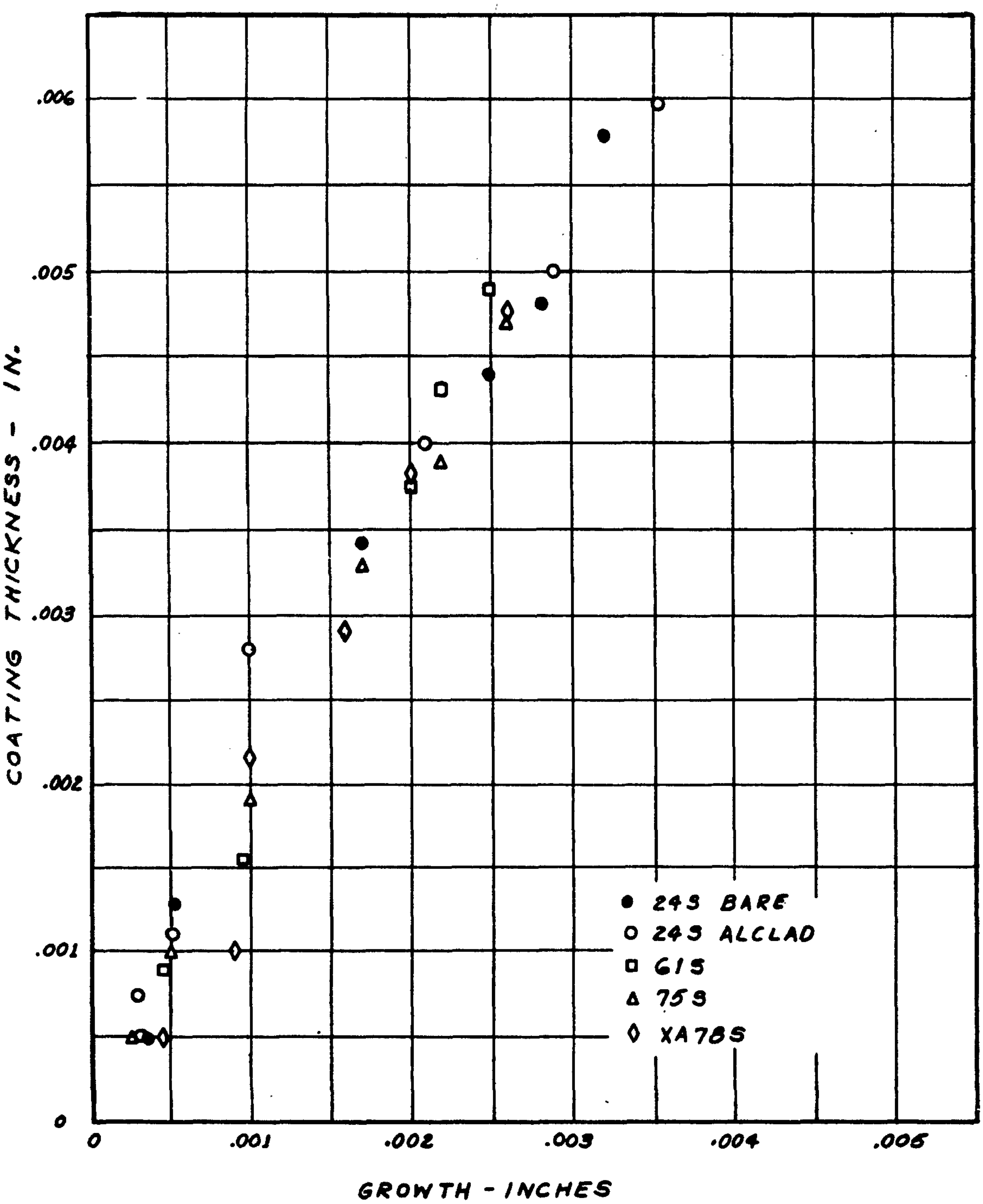
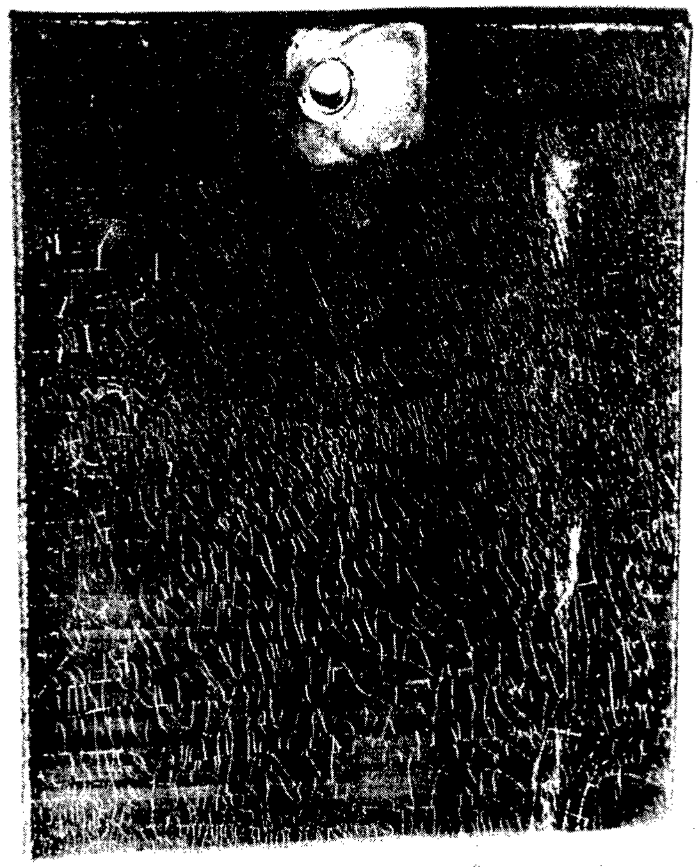


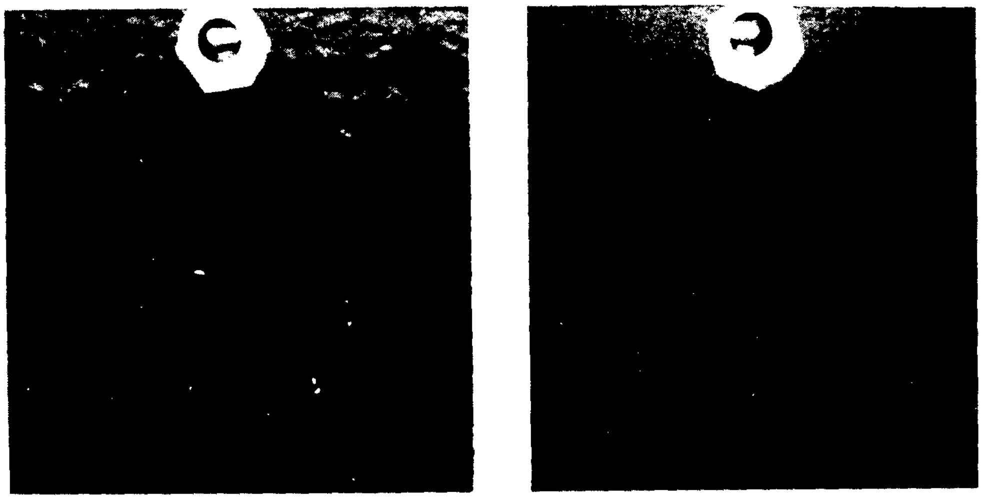
Fig. 4



COMMERCIALLY PURE ALUMINUM SHEET WITH 0.003-INCH COATING

CRAZED PATTERN DUE TO DIFFERENTIAL THERMAL EXPANSION. SOME CRACKS WERE PRESENT WHEN PIECE WAS REMOVED FROM THE BATH.

Figure 5

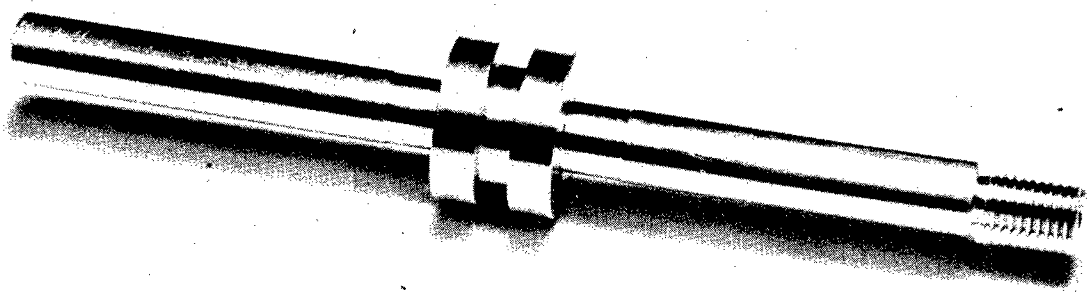


24S Alclad
0.031-inch Thick
0.0022-inch Clad
0.004-inch Coating

24S Alclad
0.082-inch Thick
0.0056-inch Clad
0.004-inch Coating

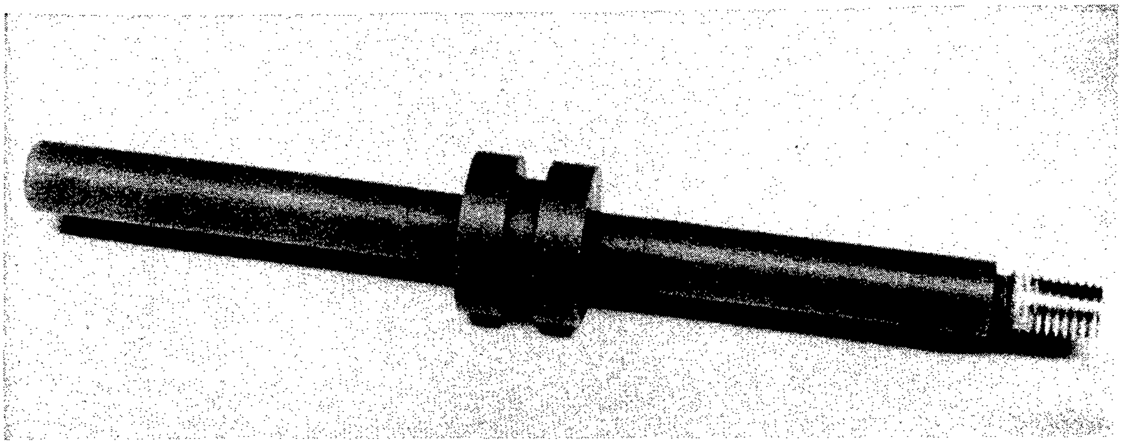
Blisters on 24S Alclad Sheet Which Occurred When the Hard Coating Thickness Exceeded the Thickness of the Cladding.

Figure 6



UNCOATED SPOOL FOR HYDRAULIC CONTROL VALUE

MADE FROM 24S AND LAPPED TO HIGH FINISH



SAME SPOOL AS ABOVE WITH 0.003-INCH COATING APPLIED

NOTE ROUGHNESS OF SURFACE. AN ALLOWANCE OF 0.0005 INCH WAS PROVIDED FOR HONING TO A SMOOTH FINISH

Figure 7

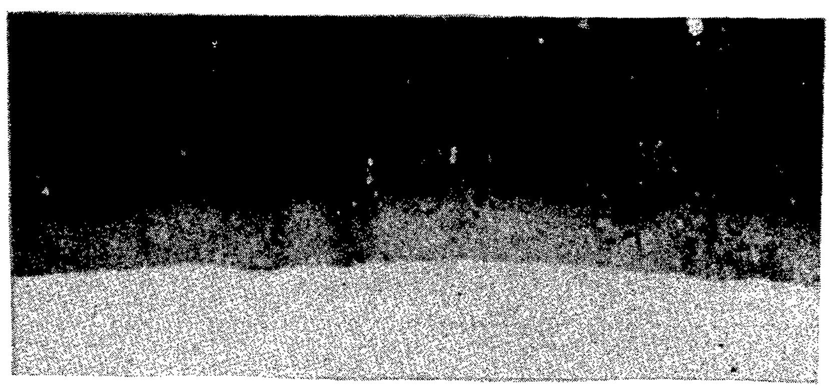
Figure 8

0.001-Inch Coating   0.003-Inch Coating   0.005-Inch Coating

"Corner Defect" Which Occurs Due to the Mechanism of the Coating Growth. The Defect is More Accentuated as the Coating Thickness Increases.

CRACKS IN 0.003-INCH COATING FORMED ON 1/16-INCH DIAMETER

300X UNETCHED

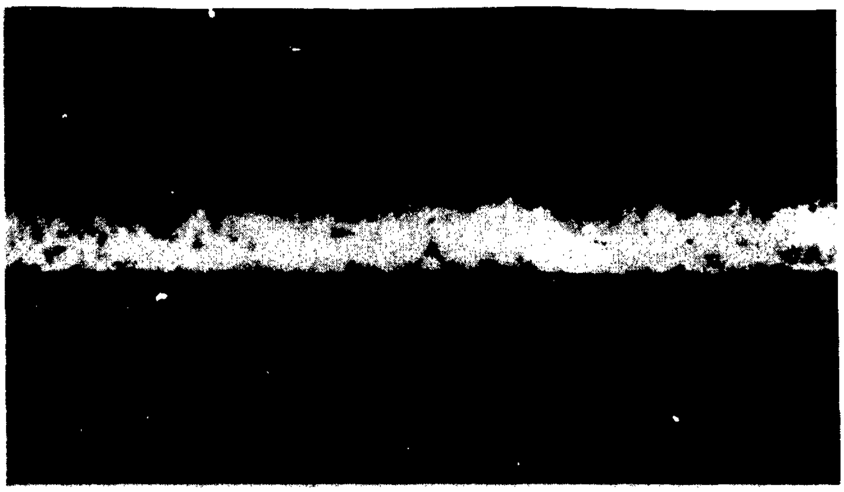


CRACKS IN 0.003-INCH COATING FORMED ON 1/4-INCH DIAMETER

300X UNETCHED

NOTE ROUNDED AREAS OF INCREASED PENETRATION AT THE BASE OF THE CRACKS WHICH SHOW THAT THEY OCCURRED DURING PROCESSING.

Figure 9

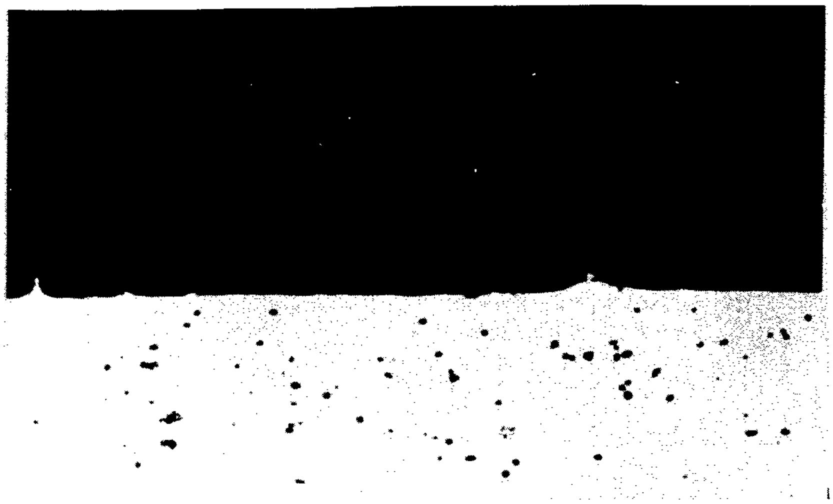


500X Polarized Light

Structure of Coating on 61S Alloy When Illuminated With Polarized Light

Except for the layer of material next to the base metal, the microstructure of the coating on 61S Alloy is homogeneous.

Figure 10



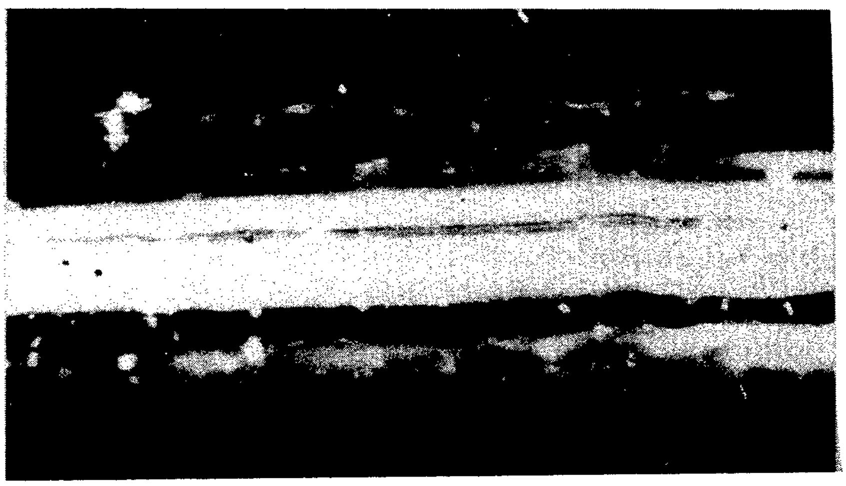
←Hard Coat

←24S Alloy

500X Unetched

Structure of Coating on 24S Alloy as Observed
When Illuminated by White Light

Figure 11



←Hard Coat

←24S Alloy

500X Polarized Light

Layer Structure of Coating on 24S Alloy
as Brought Out by Polarized Light

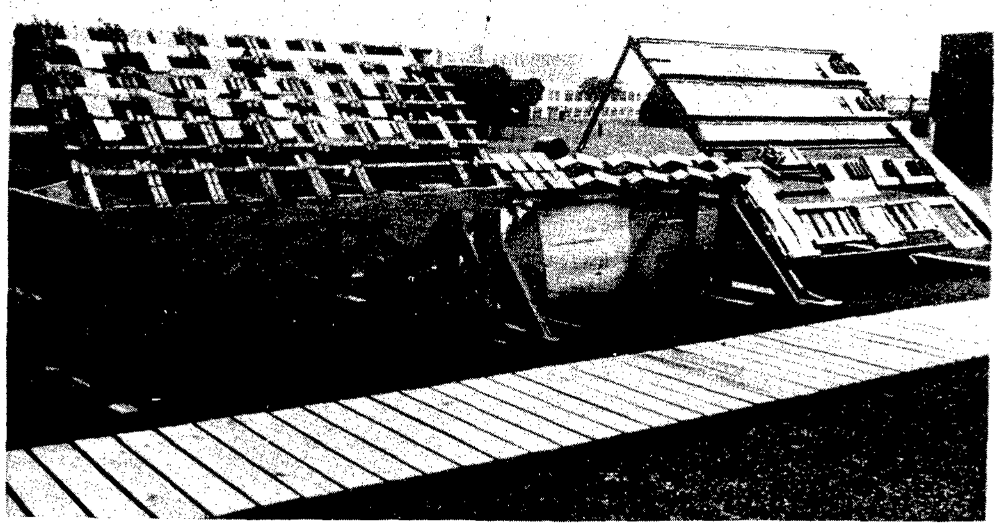
Figure 12

500X Unetched

Structure of the Coating on 356 Casting Alloy

The free silicon in the cast structure remains undisturbed except for an expansion perpendicular to the interface.

Figure 13



Exposure Rack on the Roof of Cornell Aeronautical Laboratory
Which is Located in a Semi-Industrial Atmosphere

Figure 14

ABRASION RESISTANCE

24S ALCLAD

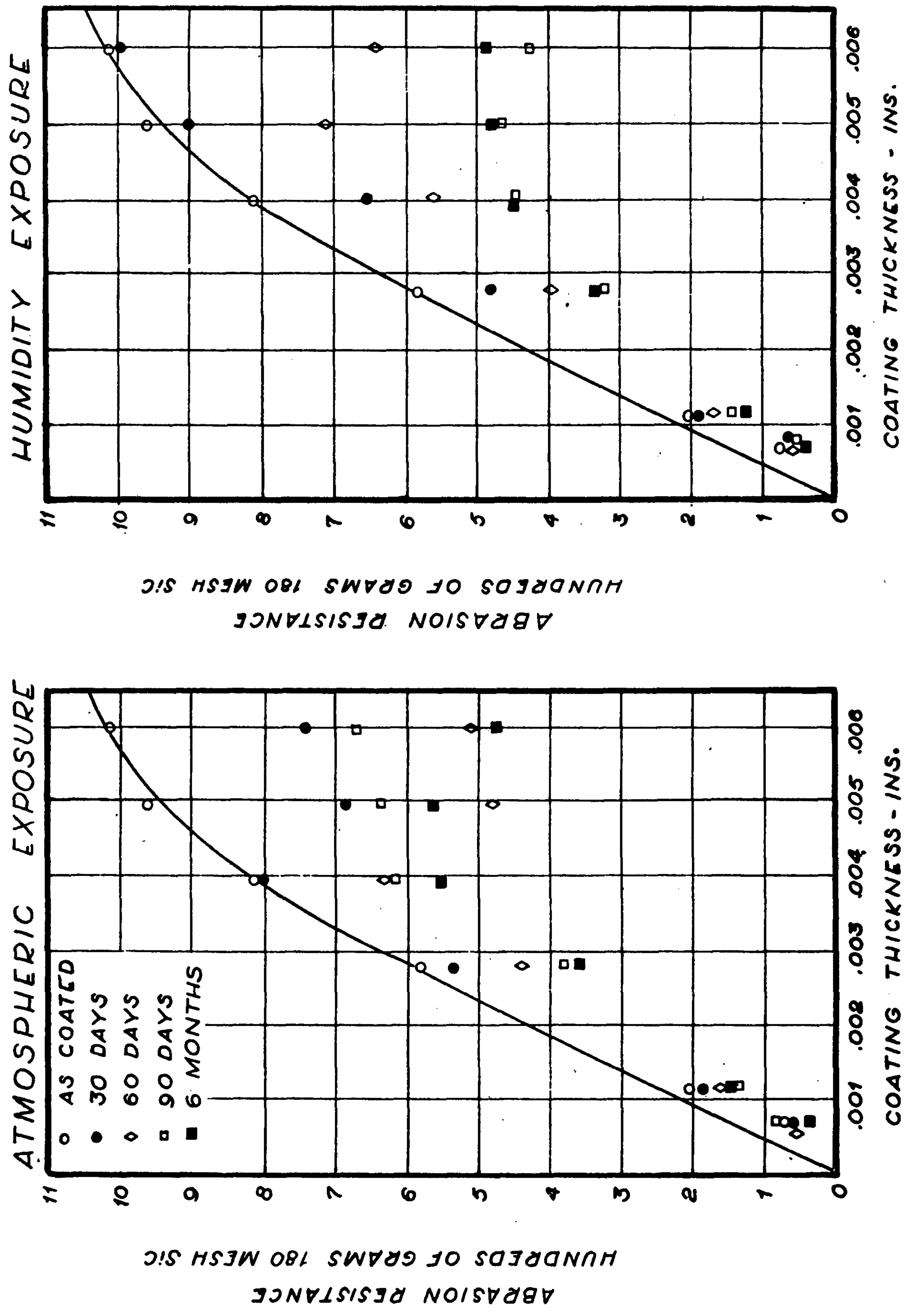


FIG. 15

ABRASION RESISTANCE
24S BARE

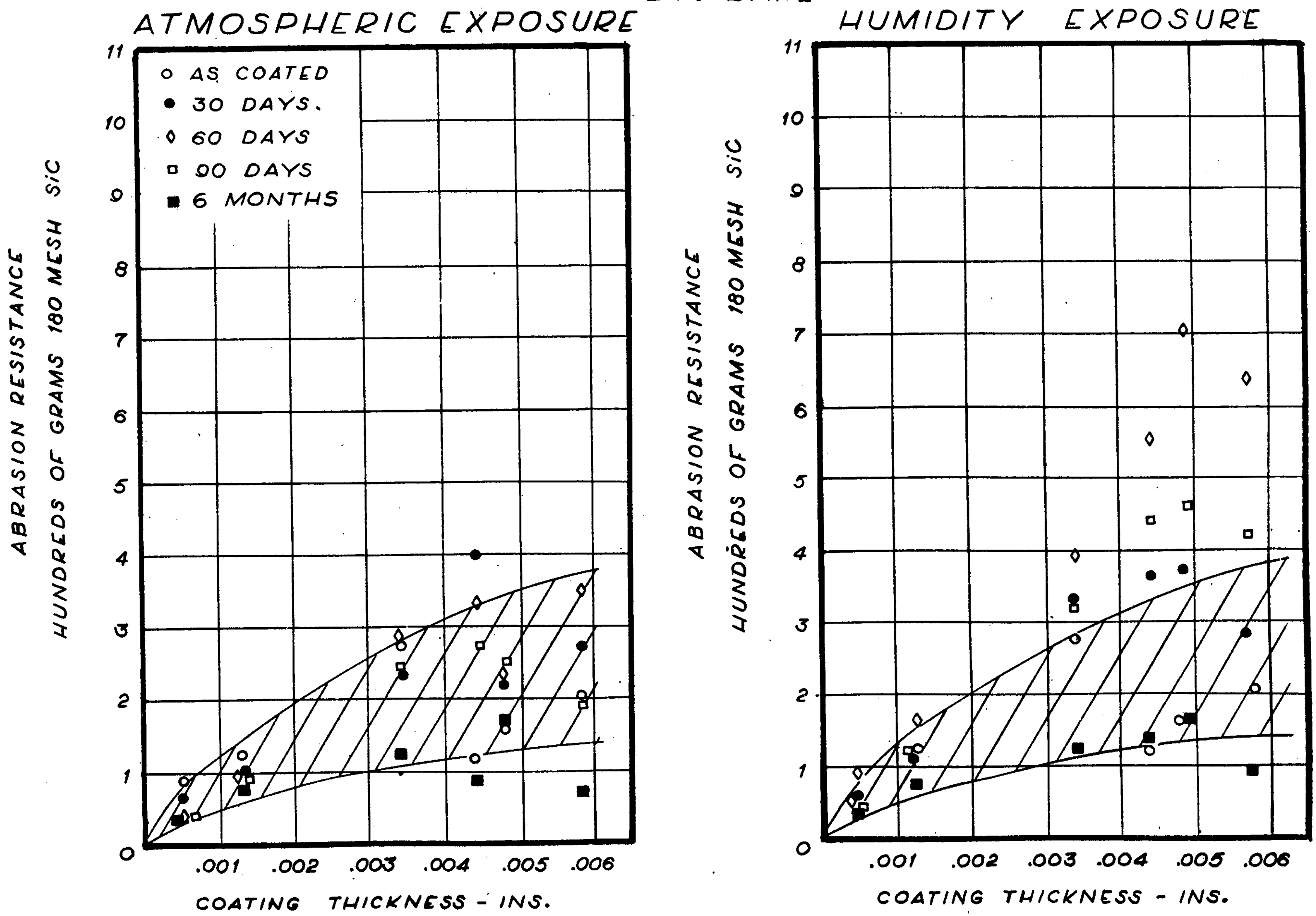


FIG. 16

ABRASION RESISTANCE
75S

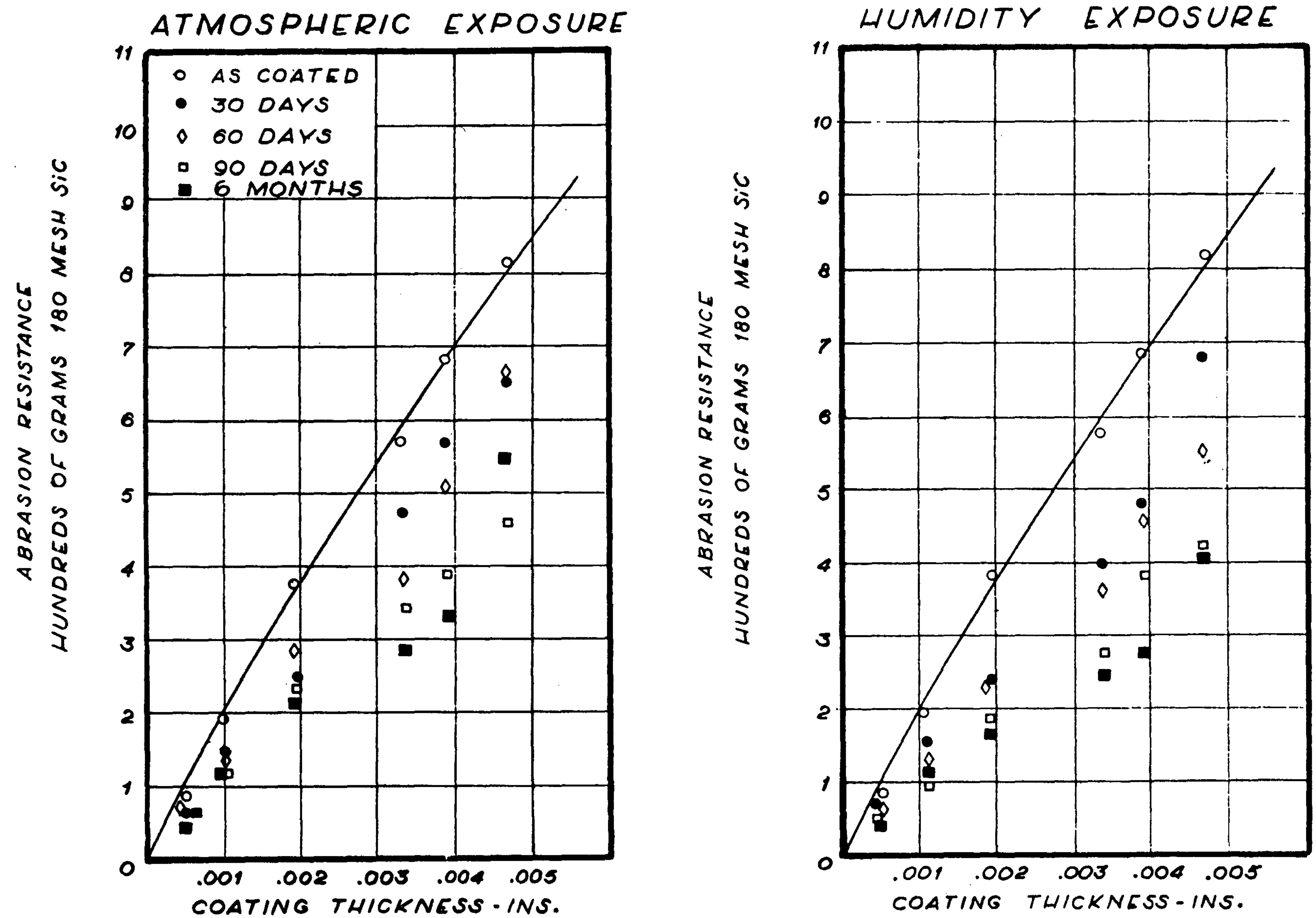
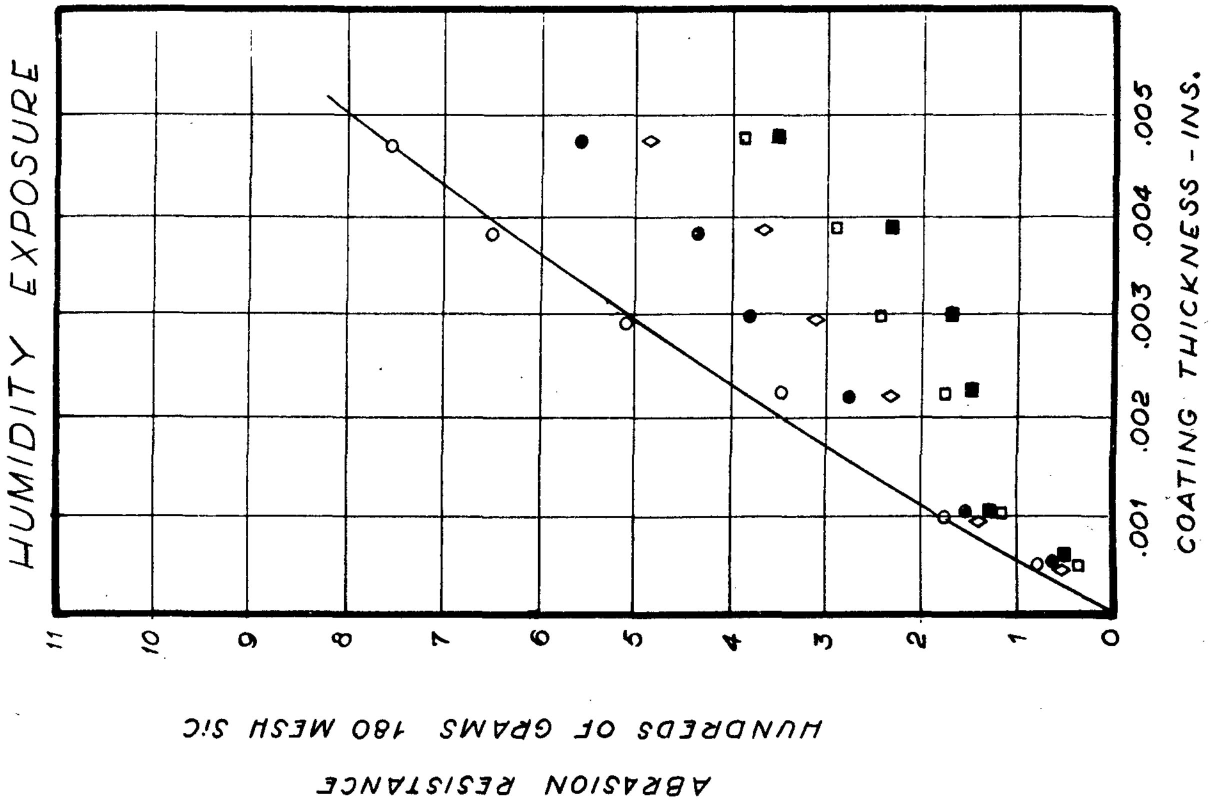


FIG. 17

ABRASION RESISTANCE
XA78S



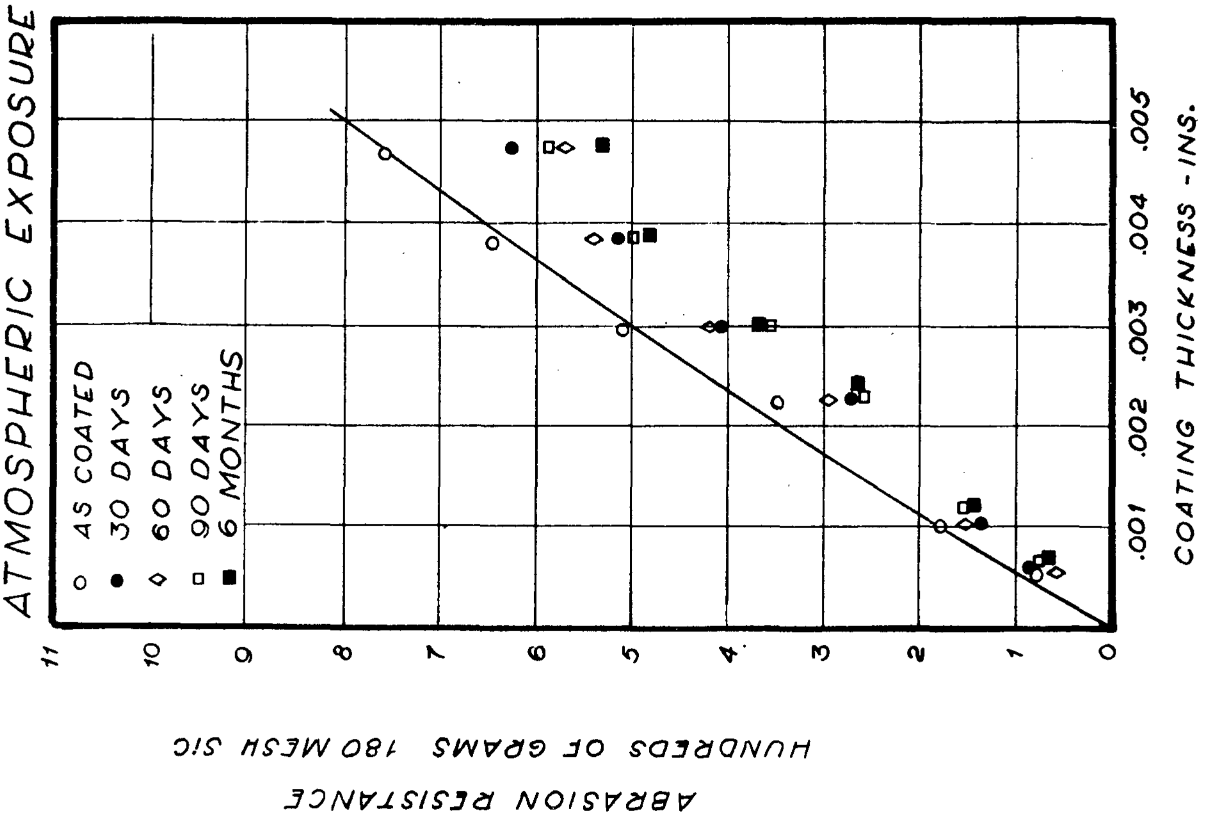


FIG. 18

ABRASION RESISTANCE
61S

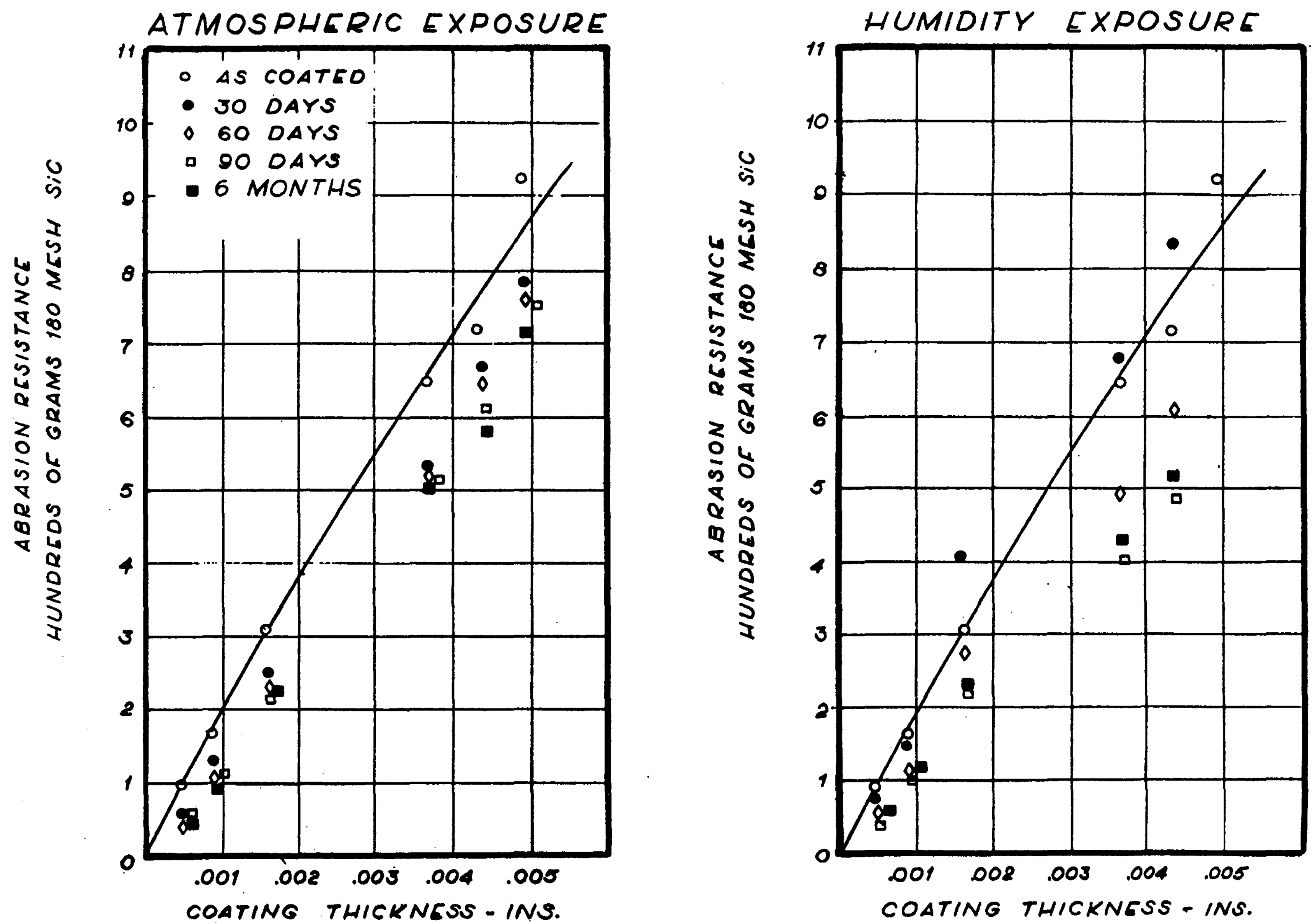


FIG. 19

ABRASION RESISTANCE
220 ALLOY

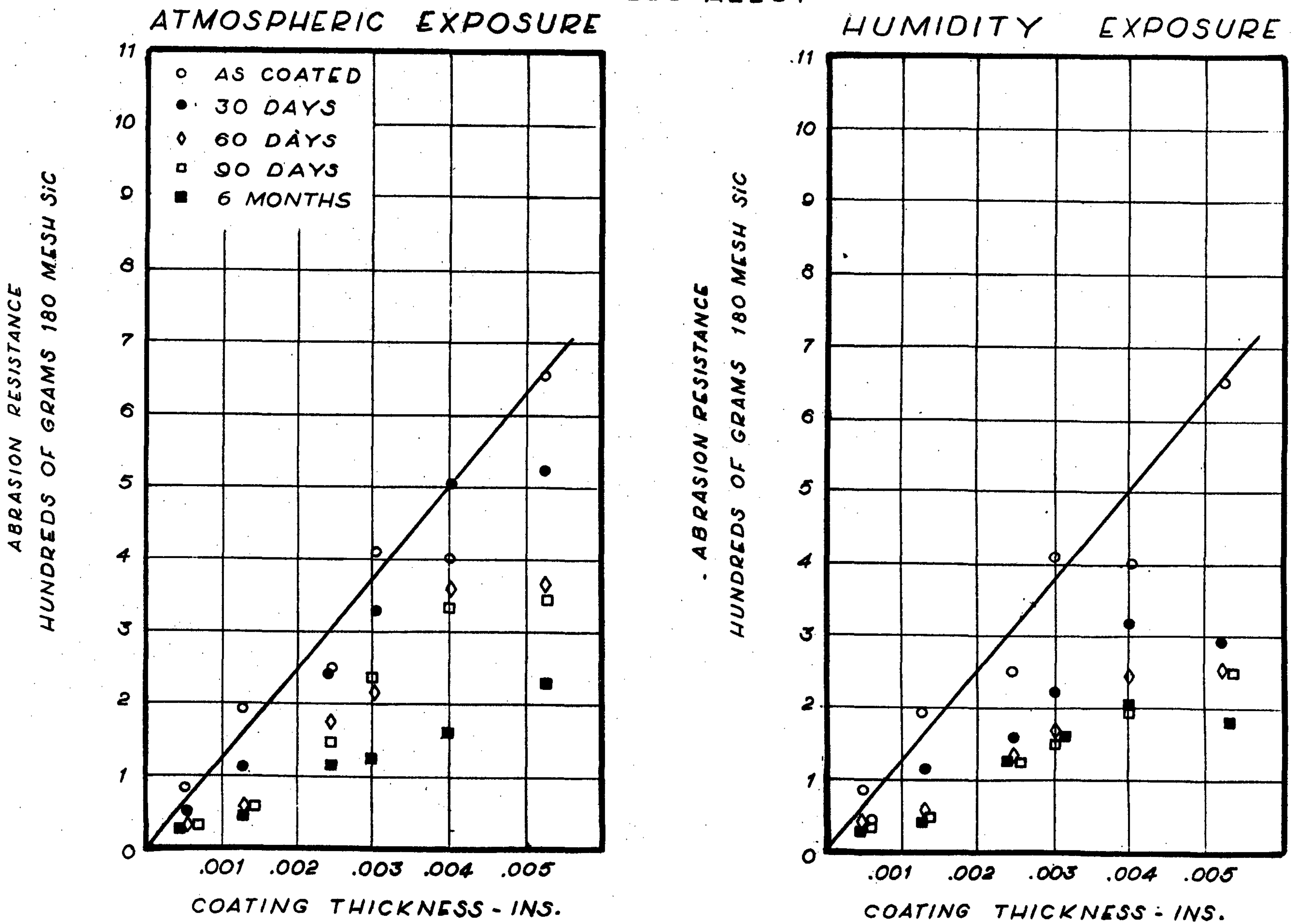


FIG. 20

ABRASION RESISTANCE
356 ALLOY

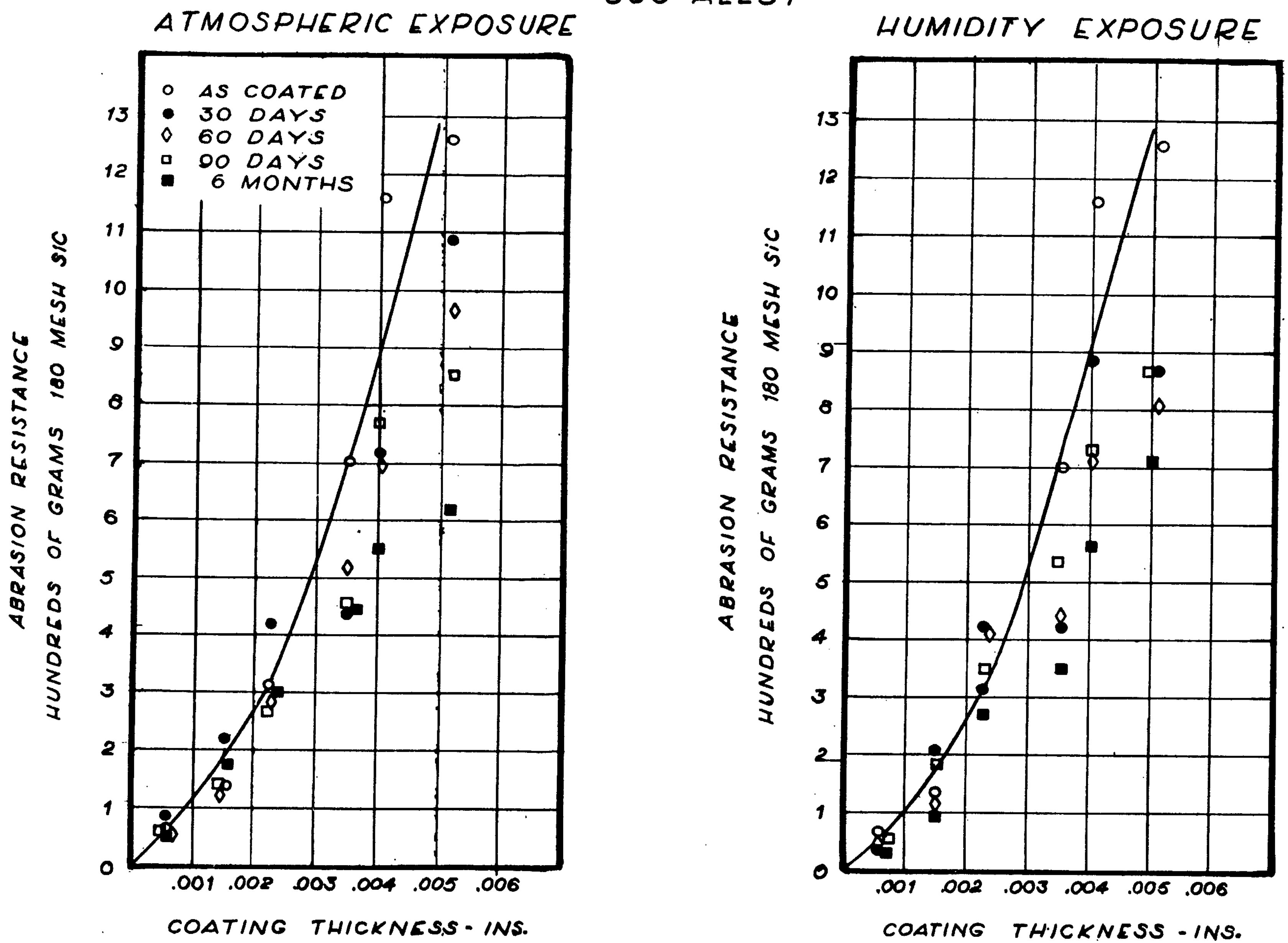


FIG. 21

DIELECTRIC STRENGTH

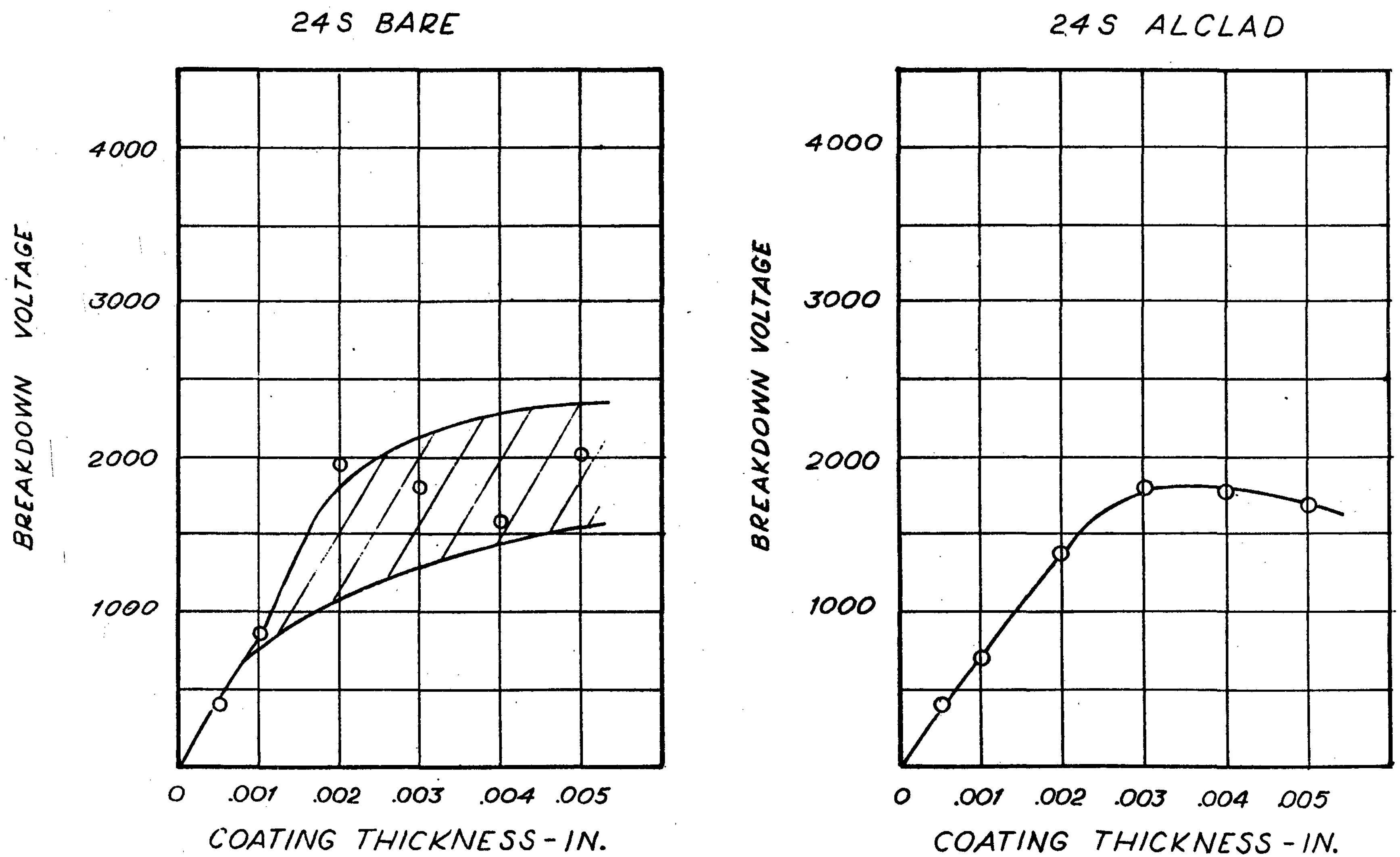


FIG. 22

DIELECTRIC STRENGTH

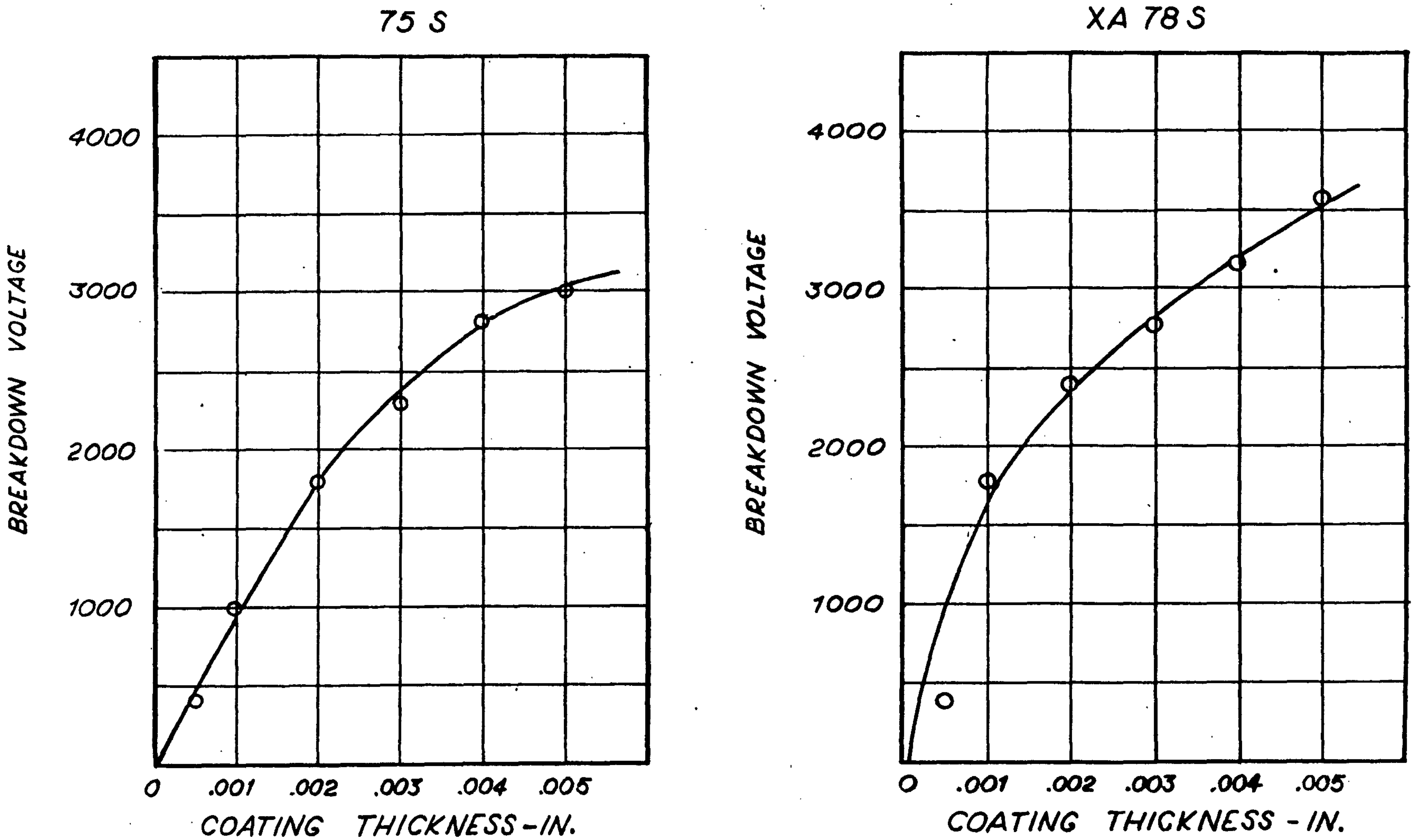


FIG. 23

DIELECTRIC STRENGTH

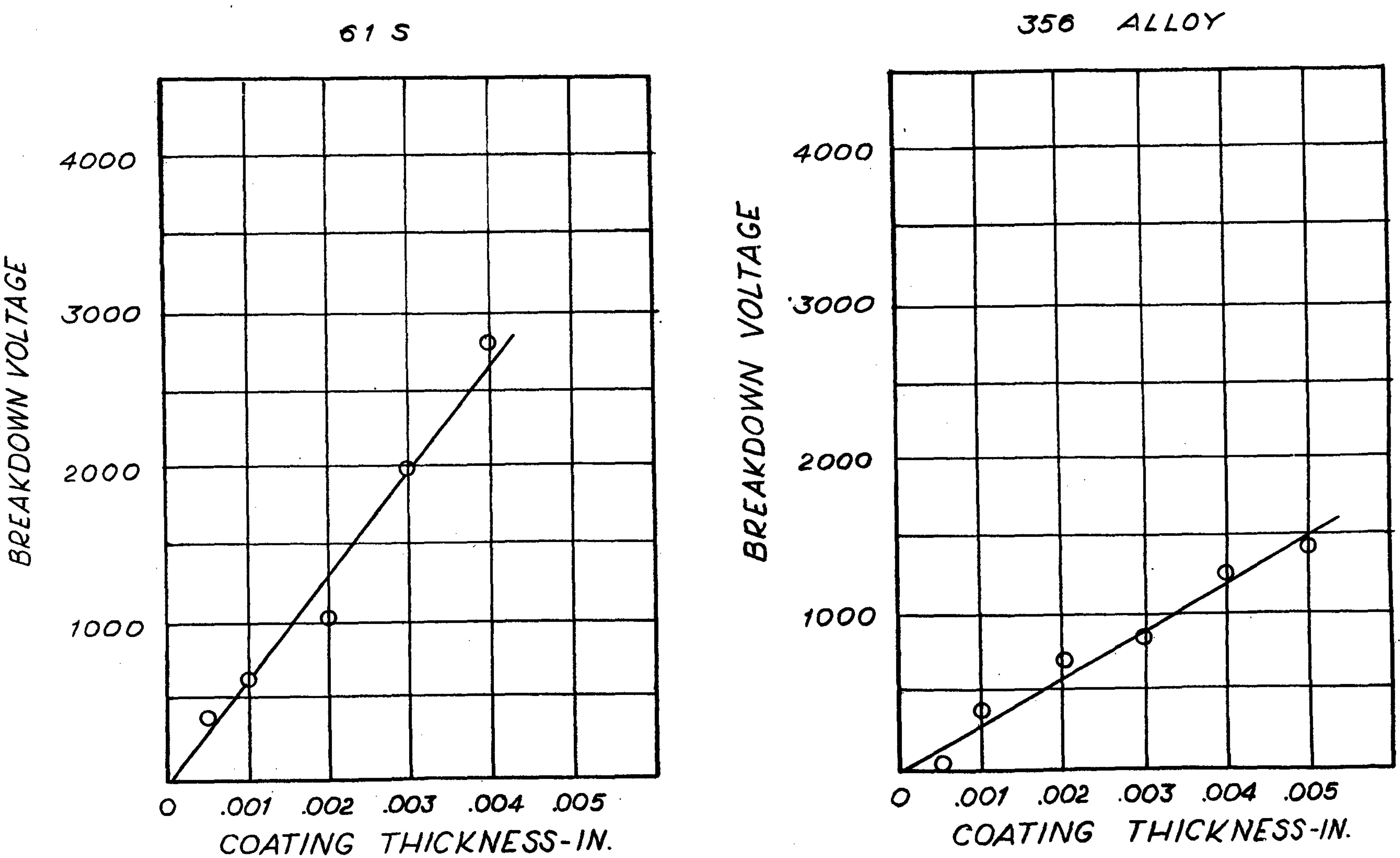


FIG. 24

DIELECTRIC STRENGTH

220 ALLOY

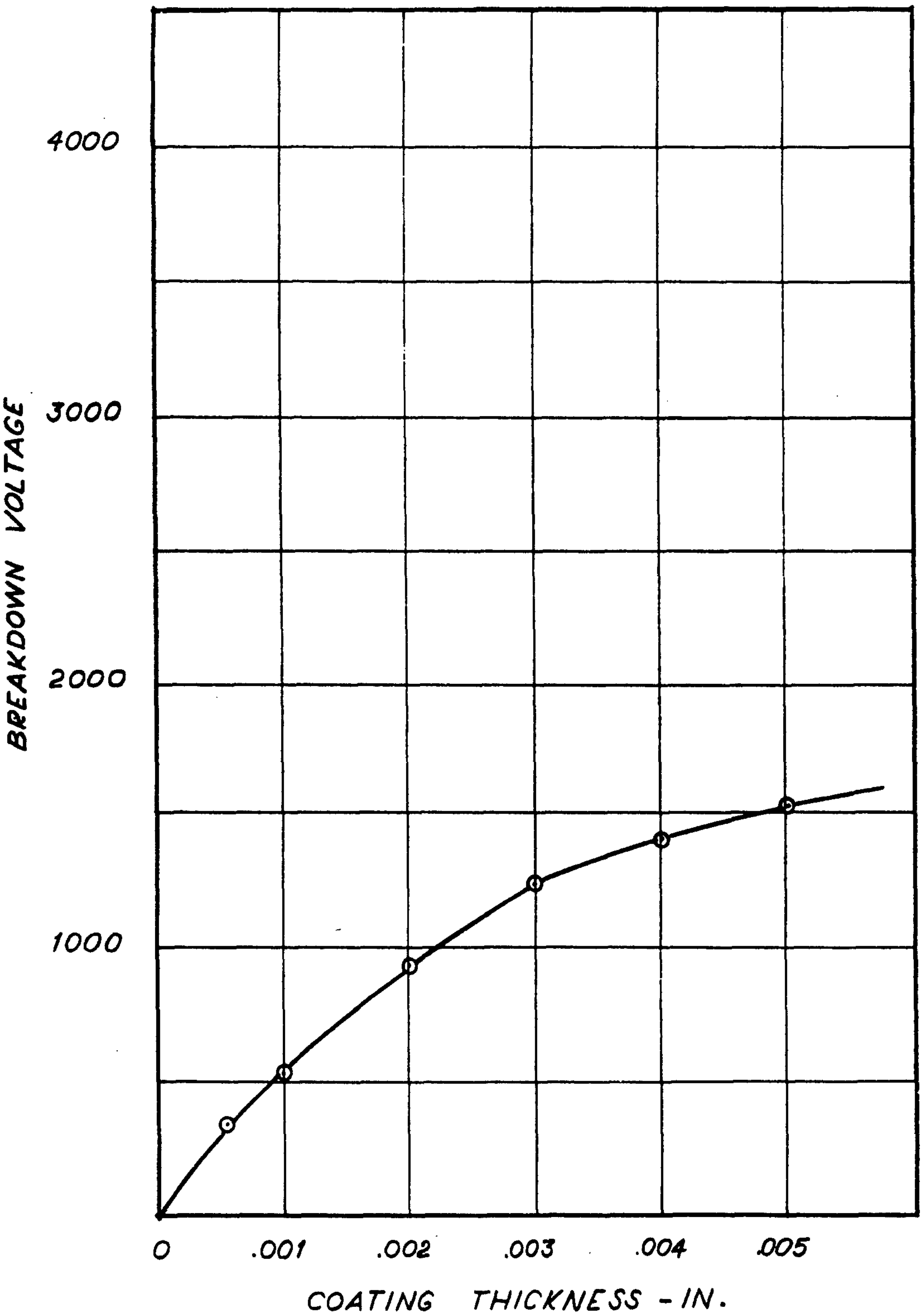


FIG. 25

EFFECT OF COATING ON FATIGUE STRENGTH
24 S ALCLAD - .053" THICK

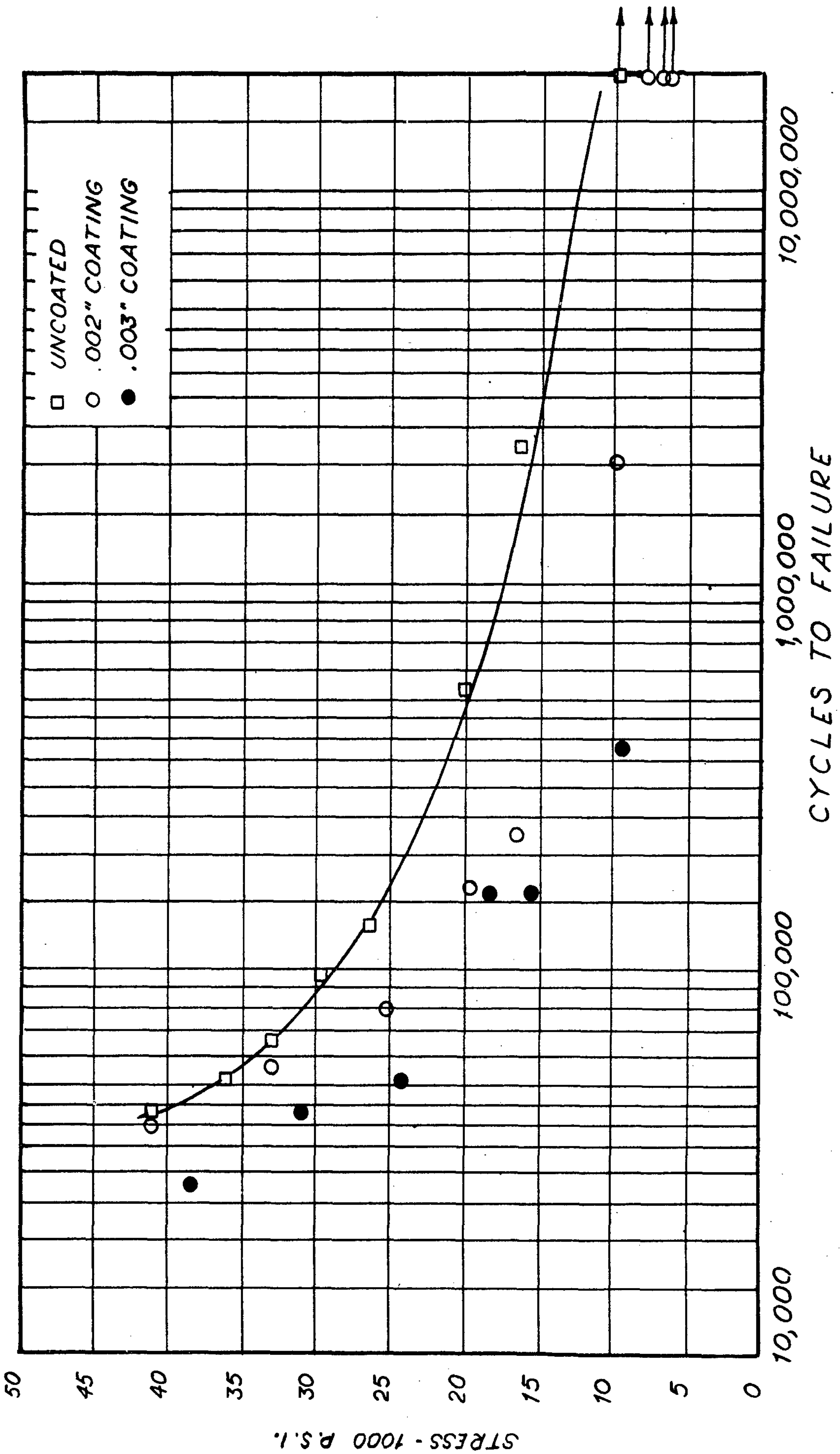


FIG. 26

EFFECT OF COATING ON FATIGUE STRENGTH
24 S — .050" THICK

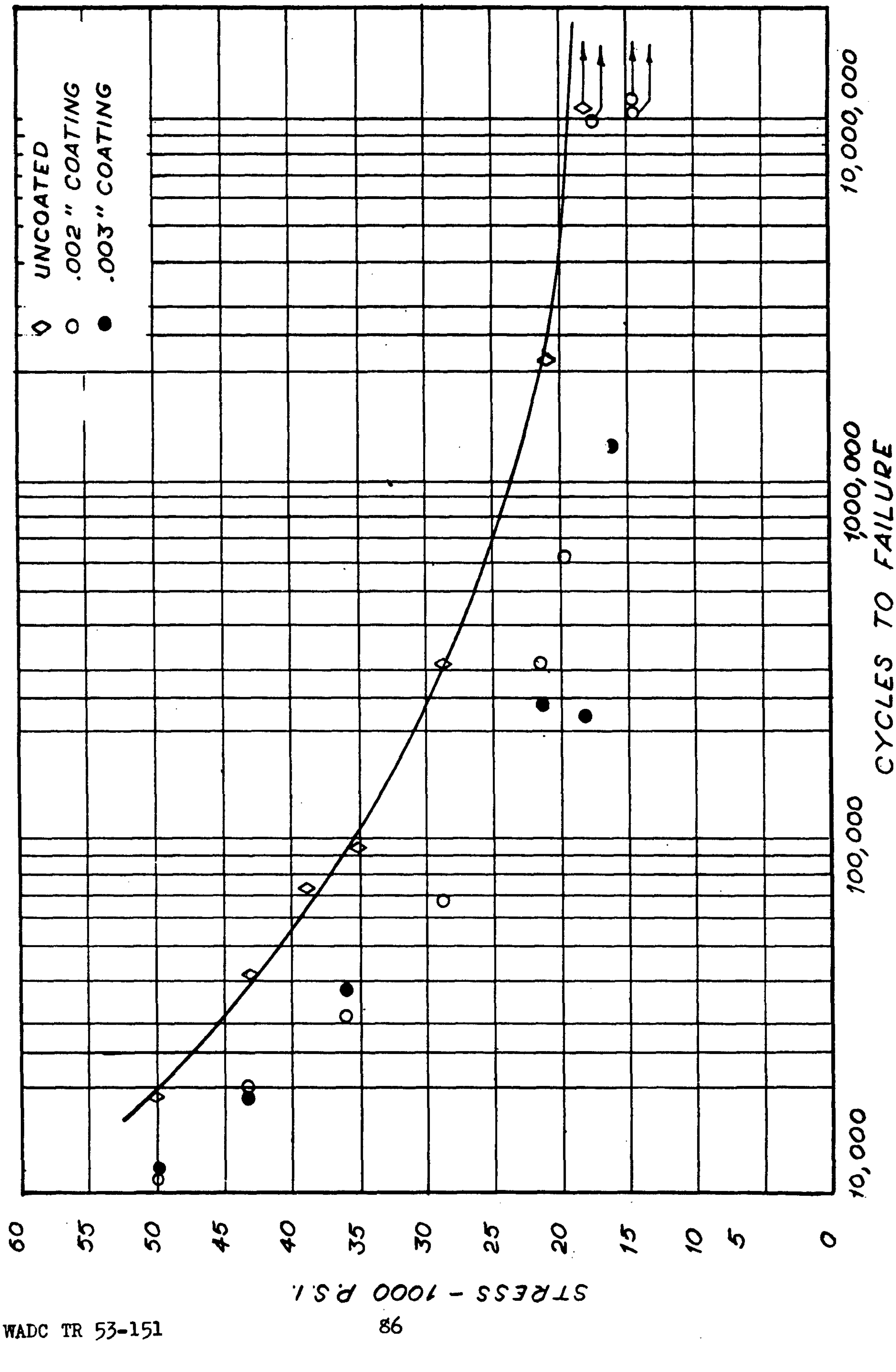


FIG. 27

EFFECT OF COATING ON FATIGUE STRENGTH
75 S – .051" THICK

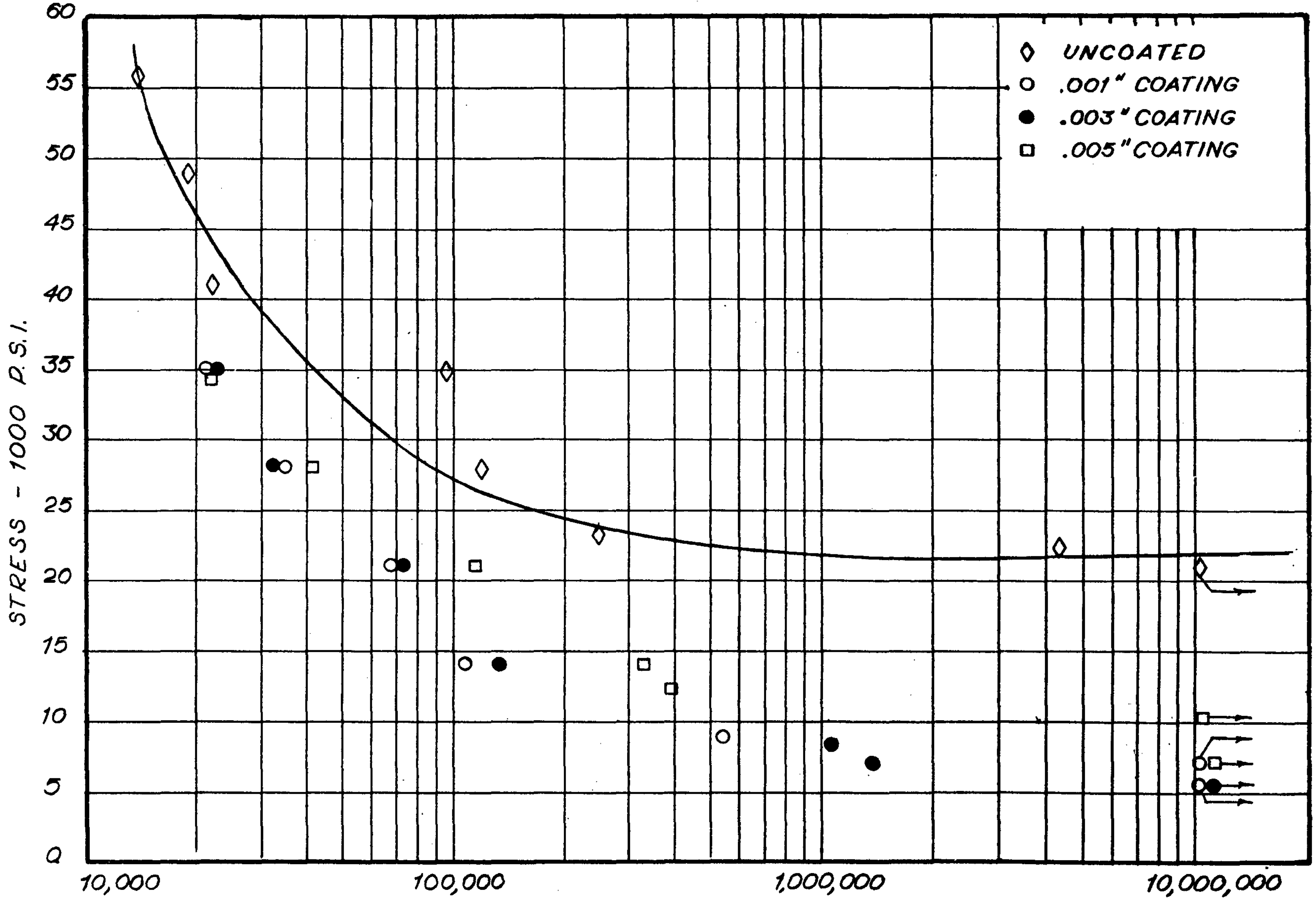


FIG. 28

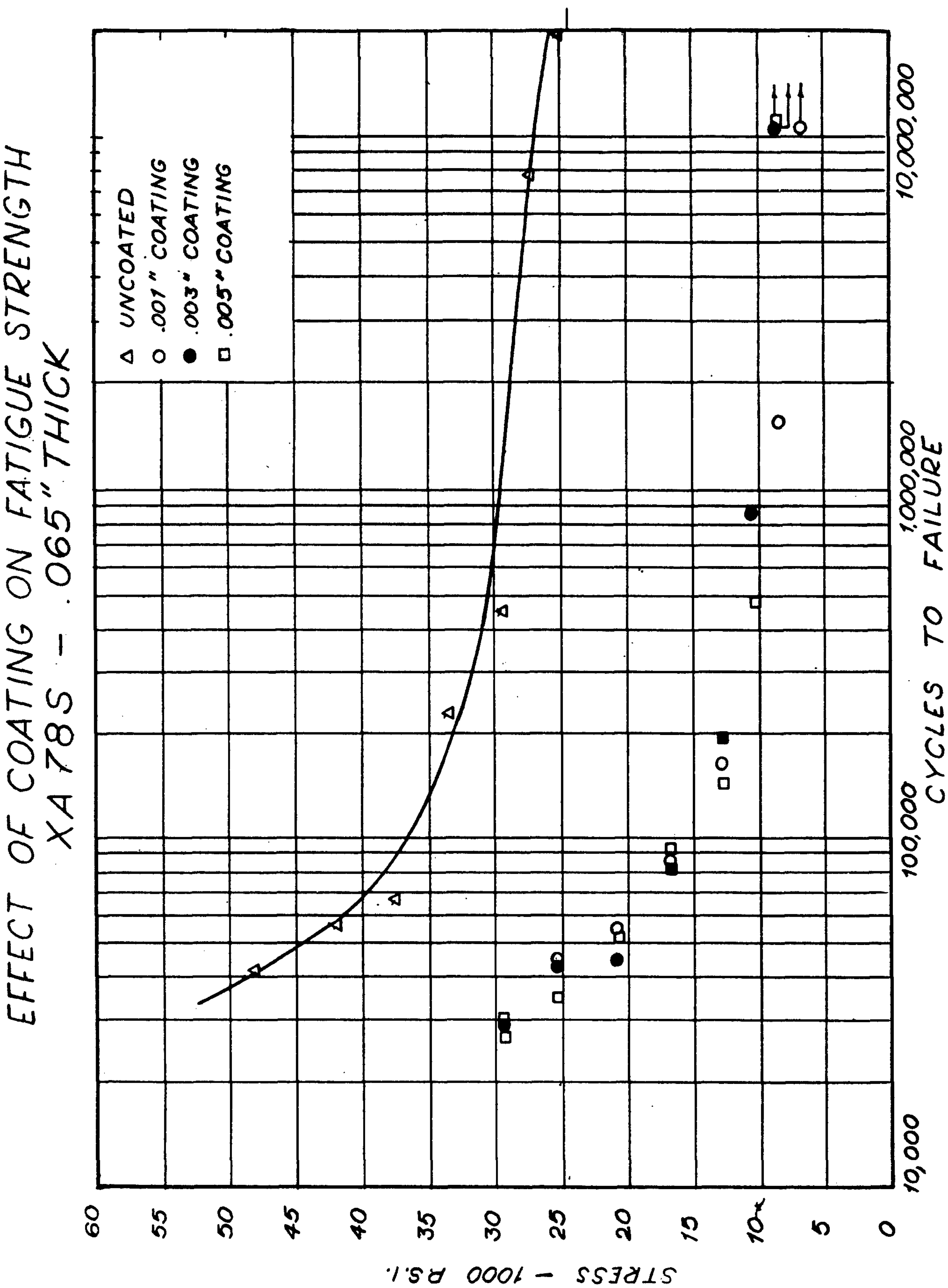

EFFECT OF COATING ON FATIGUE STRENGTH
XA 78S - .065" THICK
UNCOATED
.001" COATING
.003" COATING
.005" COATING
STRESS - 1000 P.S.I.
CYCLES TO FAILURE
60
55
50
45
40
35
30
25
20
15
10
5
0
10,000
100,000
1,000,000
10,000,000

FIG. 29

EFFECT OF COATING ON FATIGUE STRENGTH
75S ALCLAD - .040" THICK

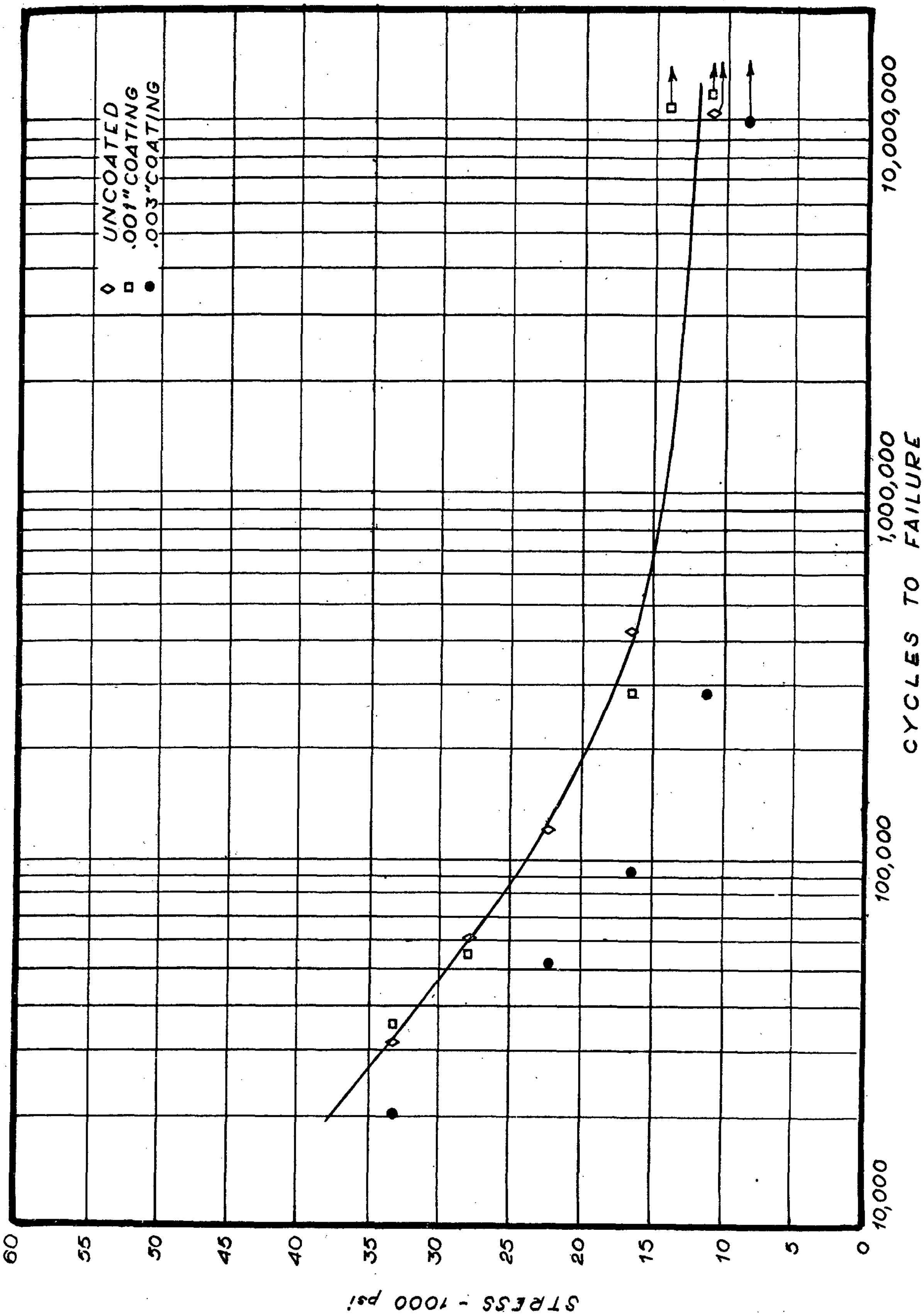


FIG. 30

EFFECT OF COATING ON FATIGUE STRENGTH

61S - .032" THICK

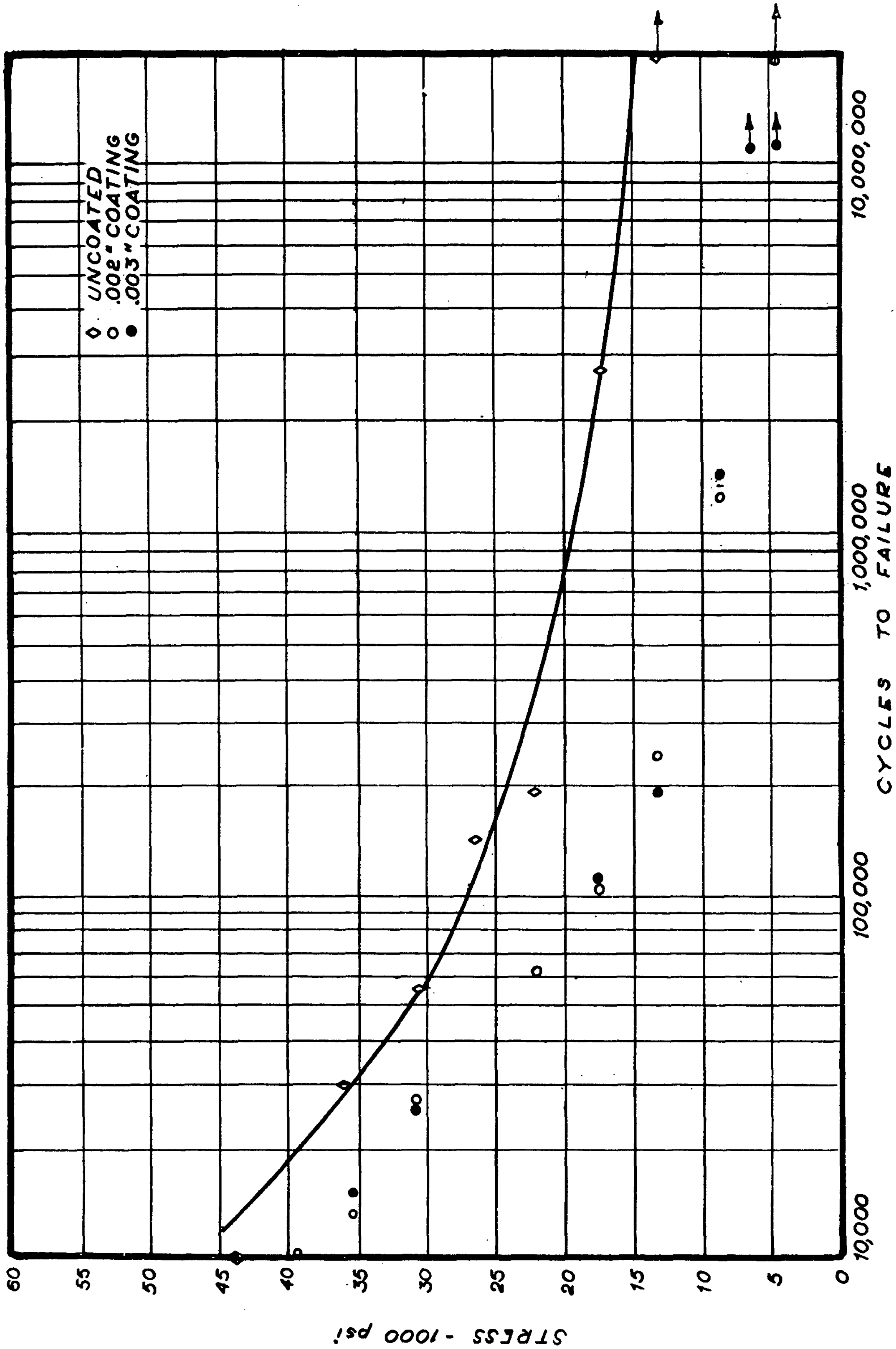


FIG. 31

EFFECT OF COATING ON FATIGUE STRENGTH

61S - .051" THICK

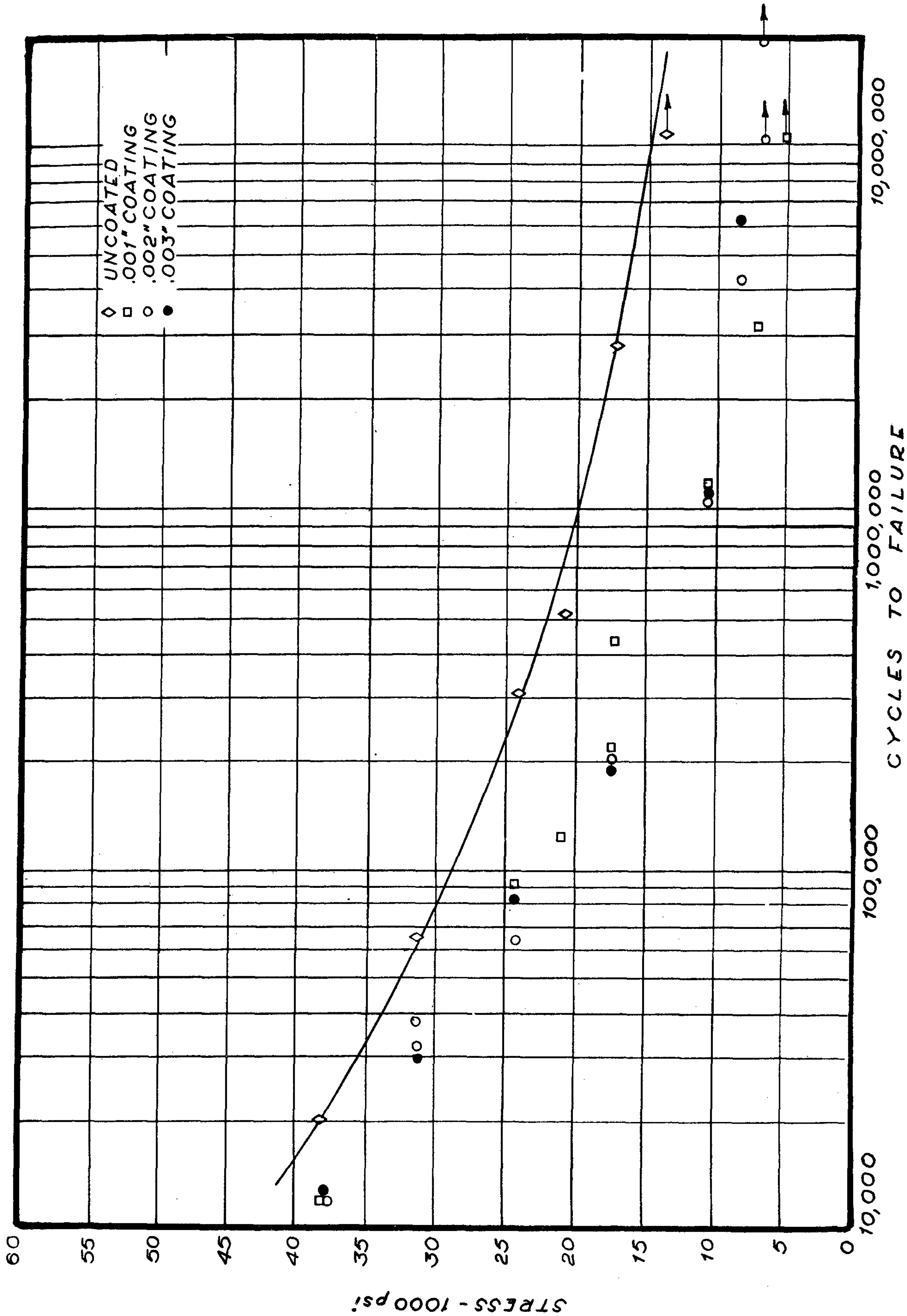


FIG. 32

EFFECT OF COATING ON FATIGUE STRENGTH

61S - .080" THICK

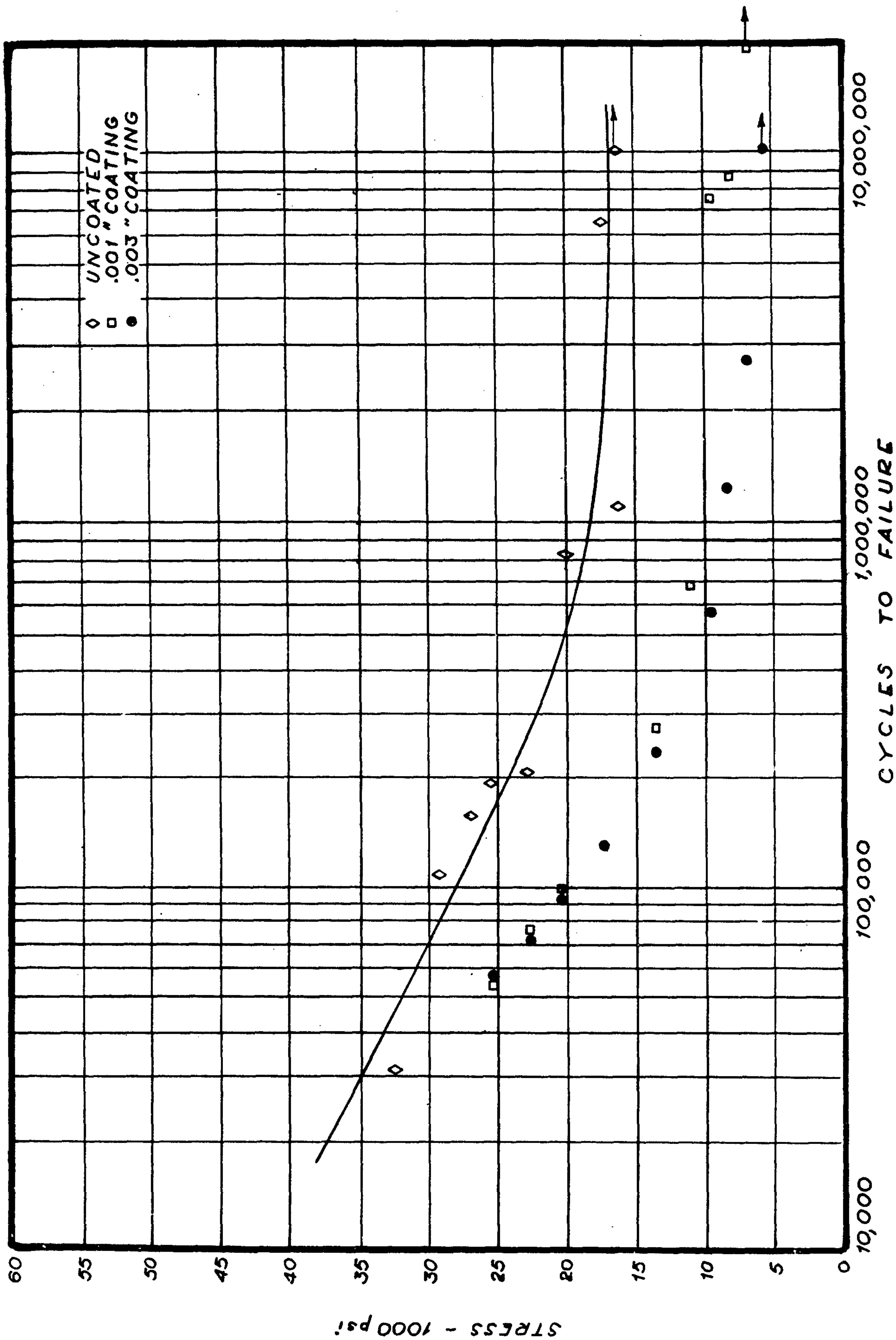


FIG. 33

EFFECT OF COATING ON FATIGUE STRENGTH
61S -.051" THICK
COATED FOR ONLY ONE-HALF LENGTH

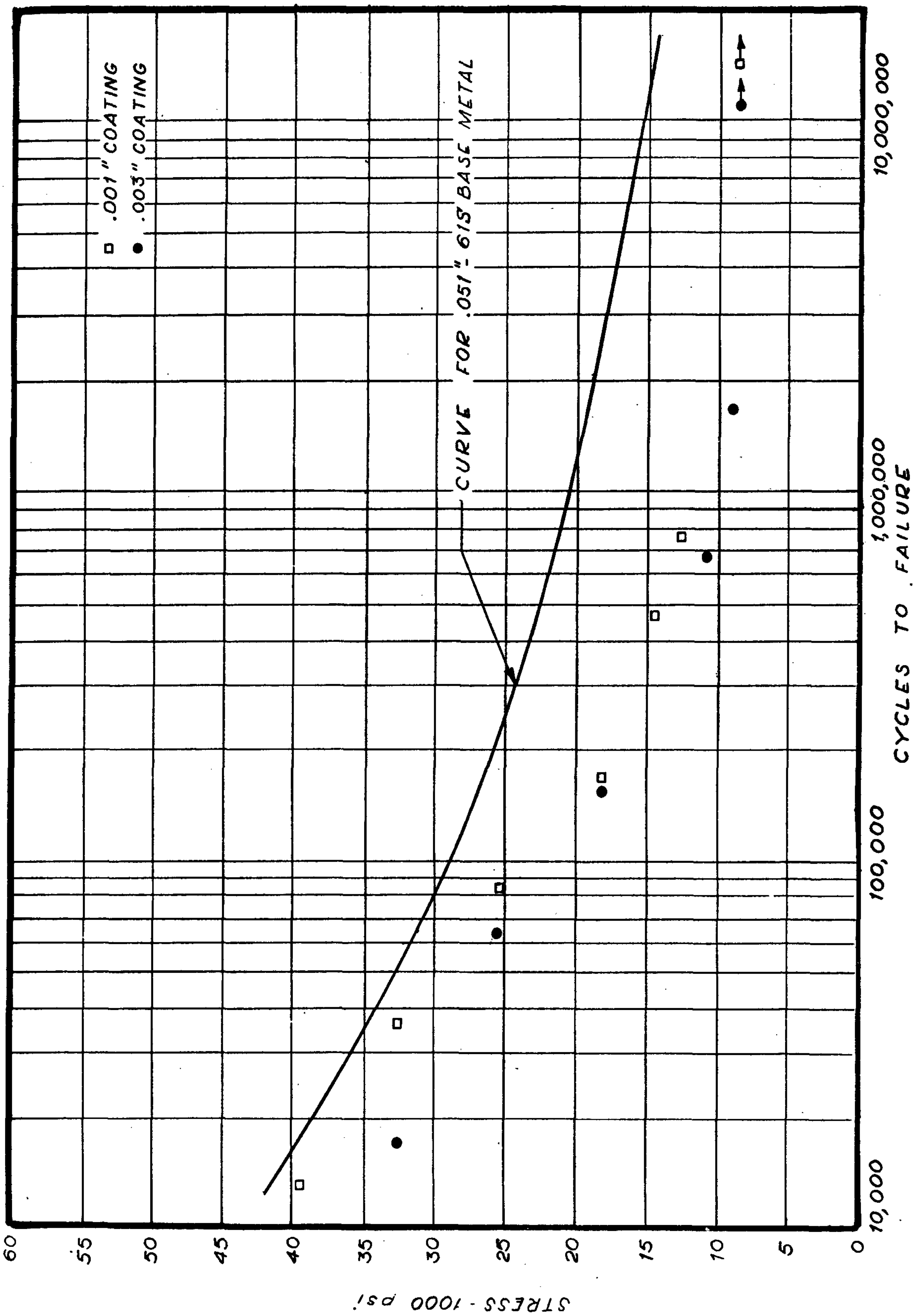


FIG. 34

EXPLANATION FOR Figure 35

Group A

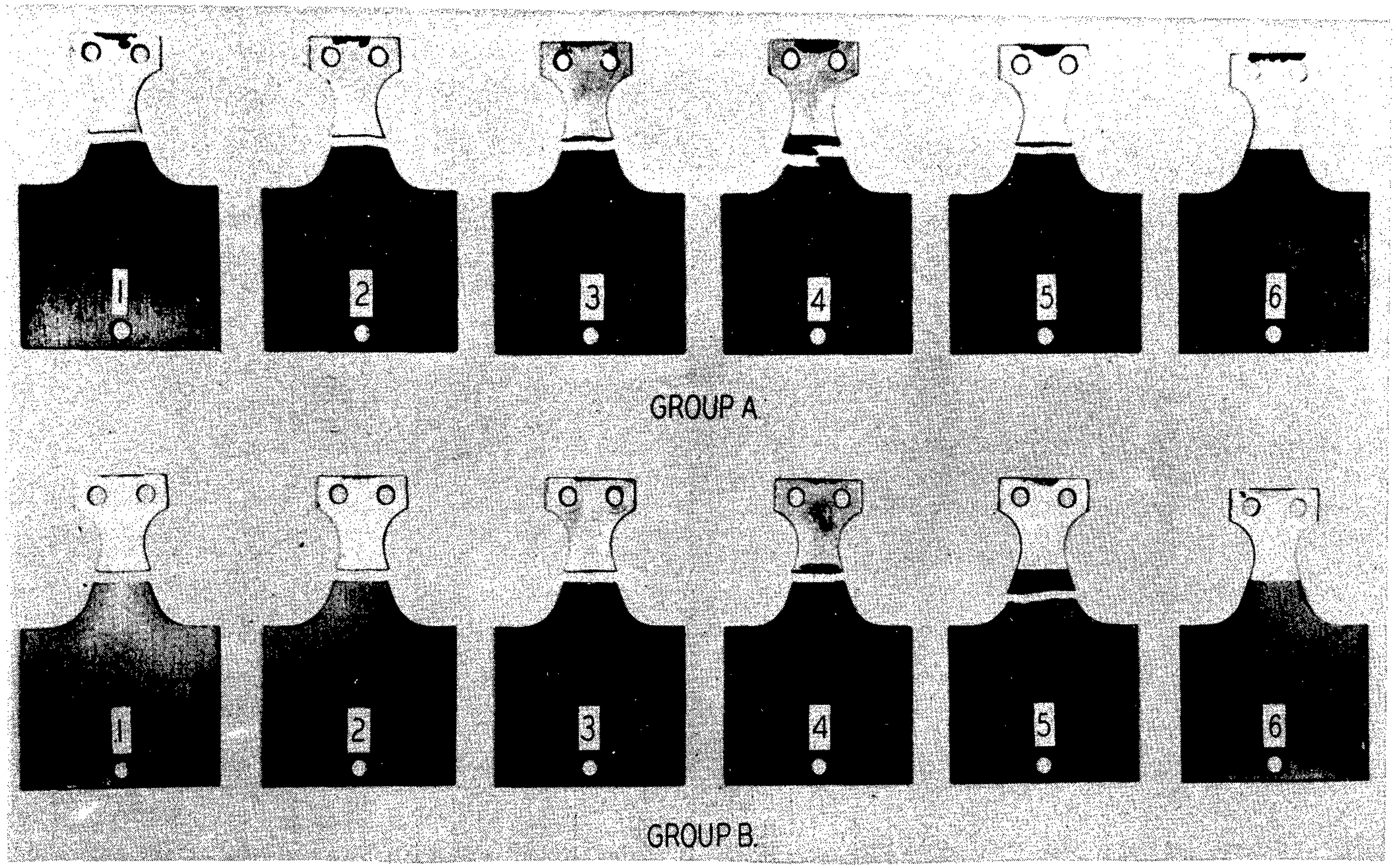
0.003-Inch Coating

	1	2	3	4	5	6
Stress Psi.	32,400	25,200	18,000	10,800	9,000	7,200
Cycles to Failure	17,000	63,000	155,000	679,000	1,780,000	11,209,000

Group B

0.001-Inch Coating

	1	2	3	4	5	6
Stress Psi.	39,600	32,400	18,000	14,400	12,600	7,200
Cycles to Failure	13,000	36,000	165,000	473,000	751,000	14,802,000



LOCATION OF FAILURES IN 61S FATIGUE SPECIMENS COATED FOR HALF THEIR LENGTH

61S - 0.051-INCH THICK

Figure 35

EFFECT OF COATING ON FATIGUE STRENGTH
61S - .051 " THICK
SPECIMENS COATED ON ONE SIDE ONLY

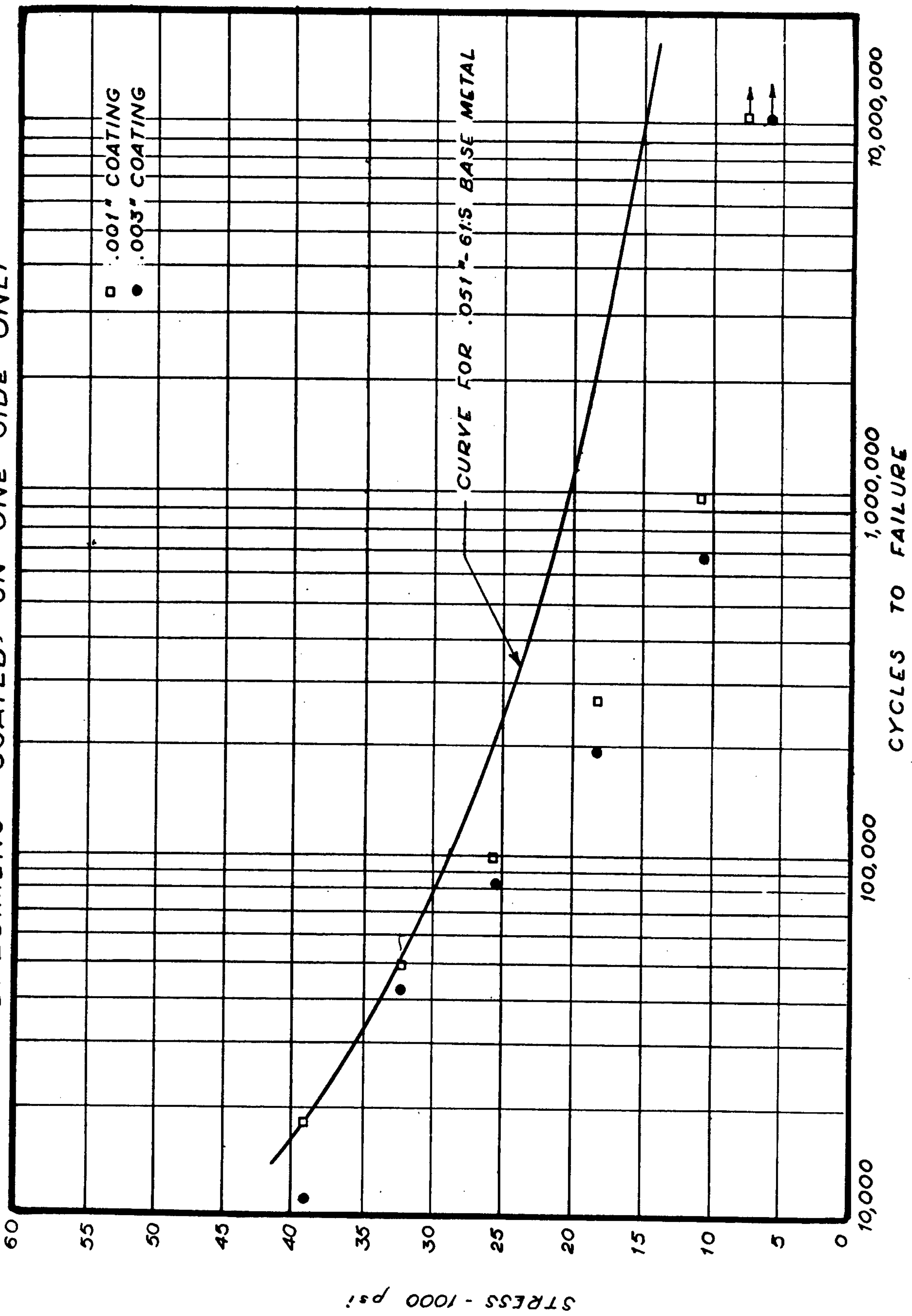


FIG. 36

EFFECT OF COATING ON FATIGUE STRENGTH

220 - .150" THICK

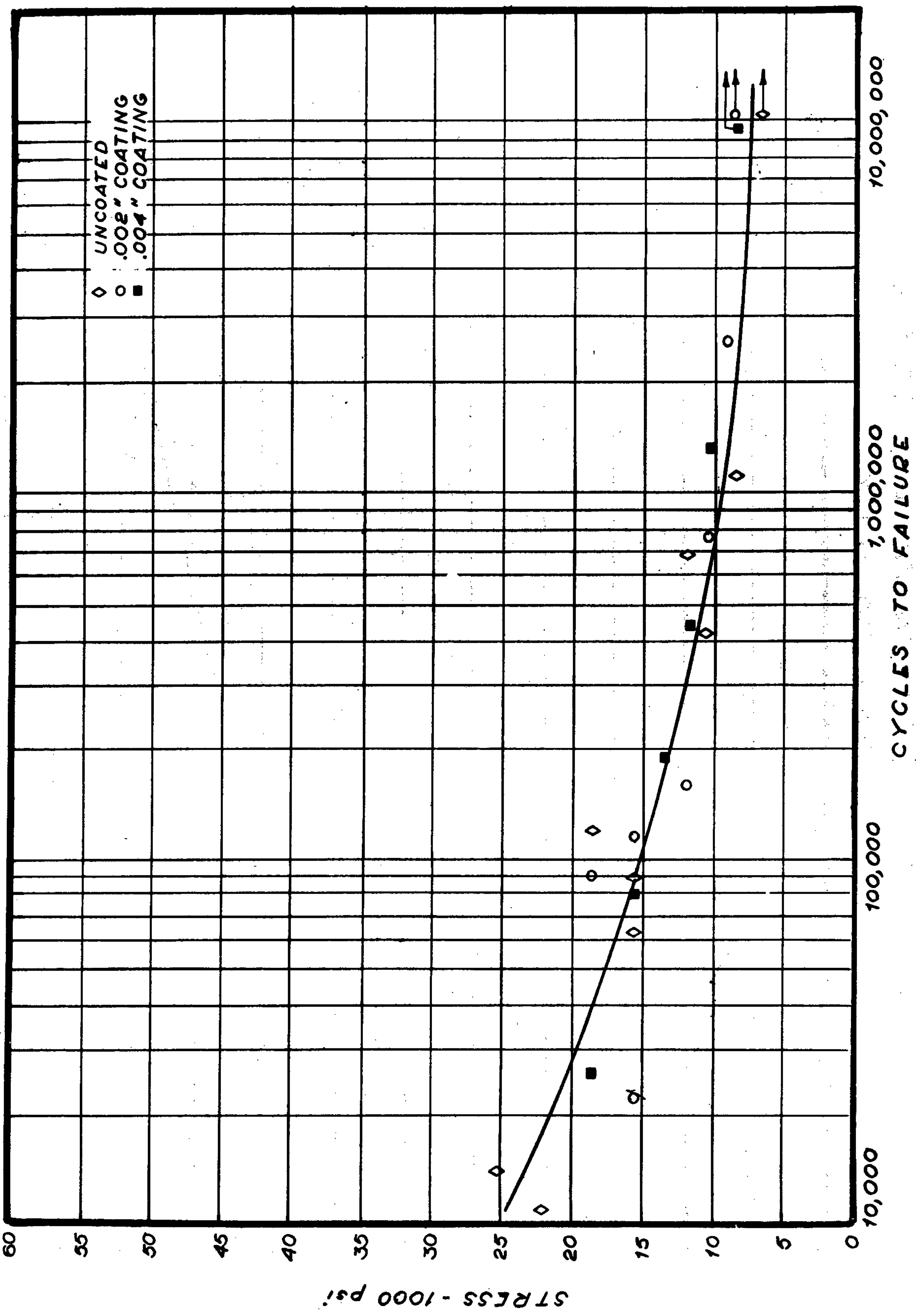


FIG. 37

EFFECT OF COATING ON FATIGUE STRENGTH
356 - .150" THICK

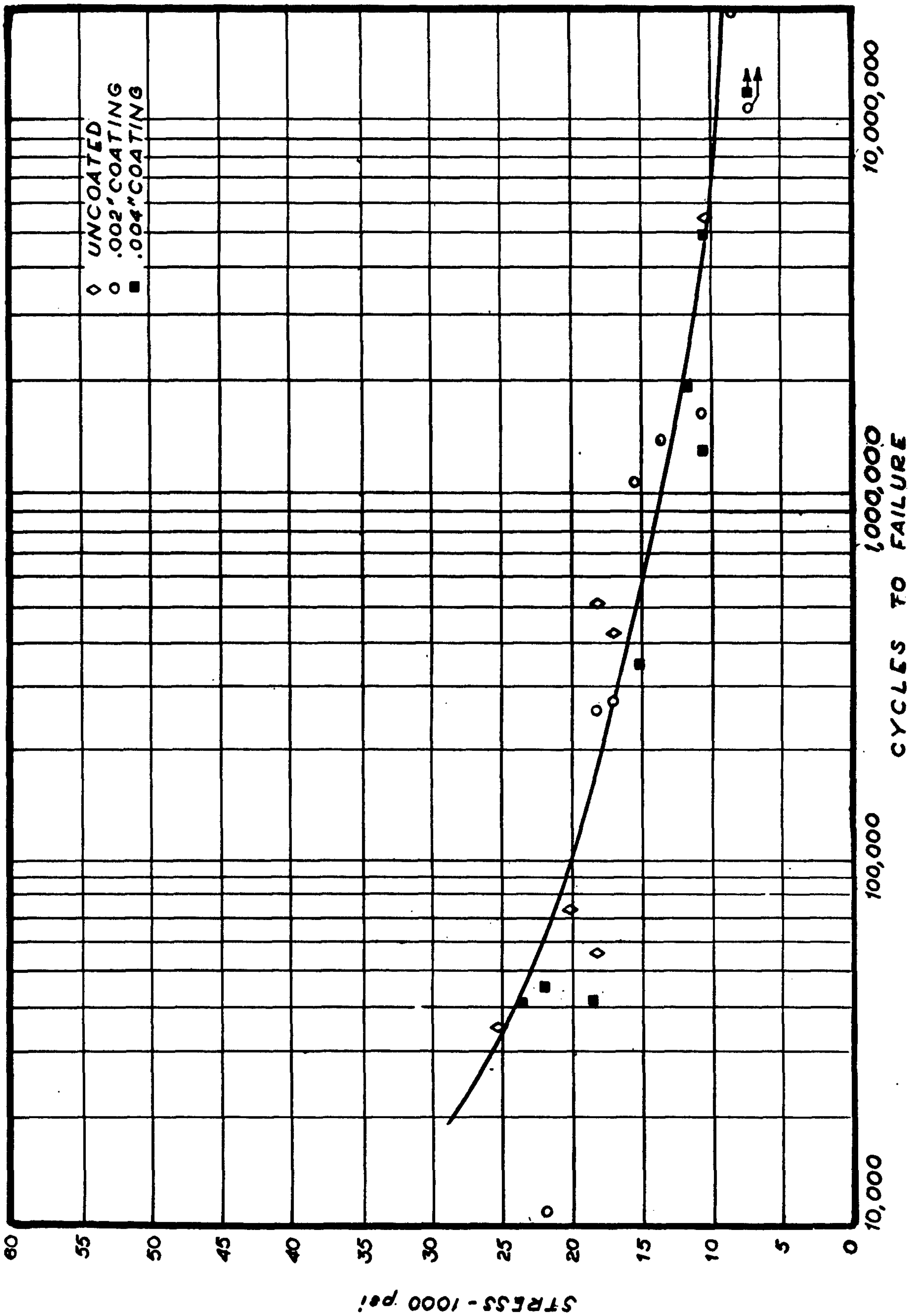
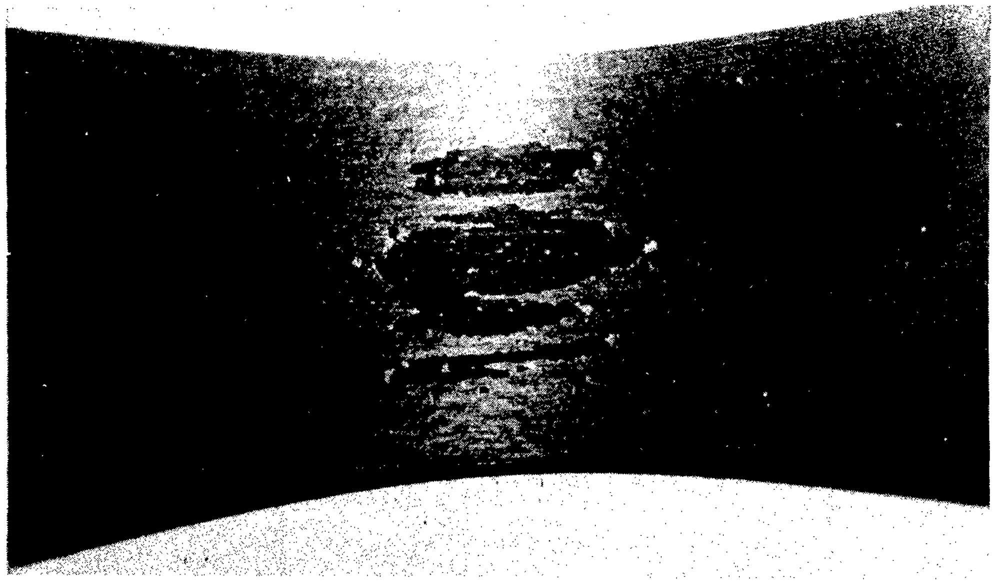
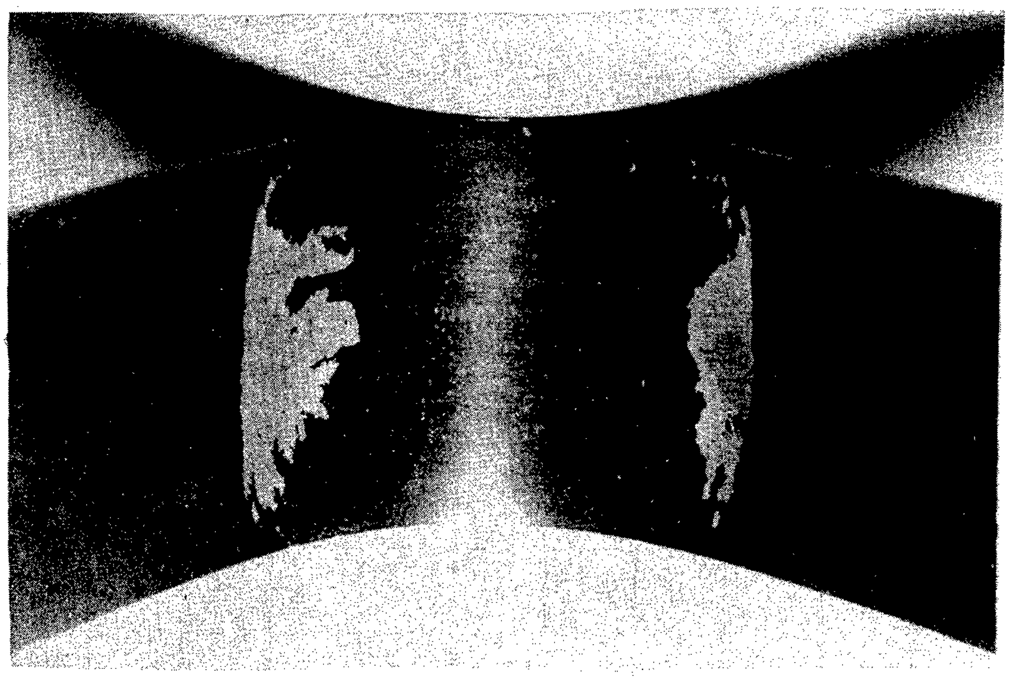


FIG. 38



Bend Test on 24S-T3 Alloy With 0.002-Inch Coating
Coating peeled off in layers.



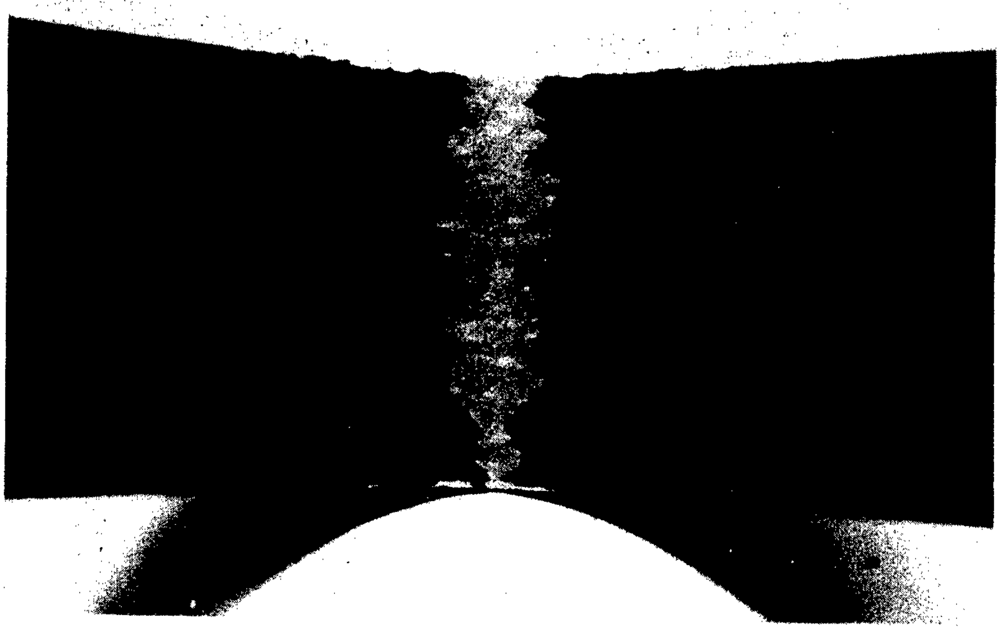
Bend Test on 24S-T3 Alloy With 0.001-Inch Coating

Outer layer has peeled off for a considerable distance while layer in contact with base metal has pitted only slightly.

Figure 39

Bend Test 24S-T3 Alloy With 0.004-Inch Coating

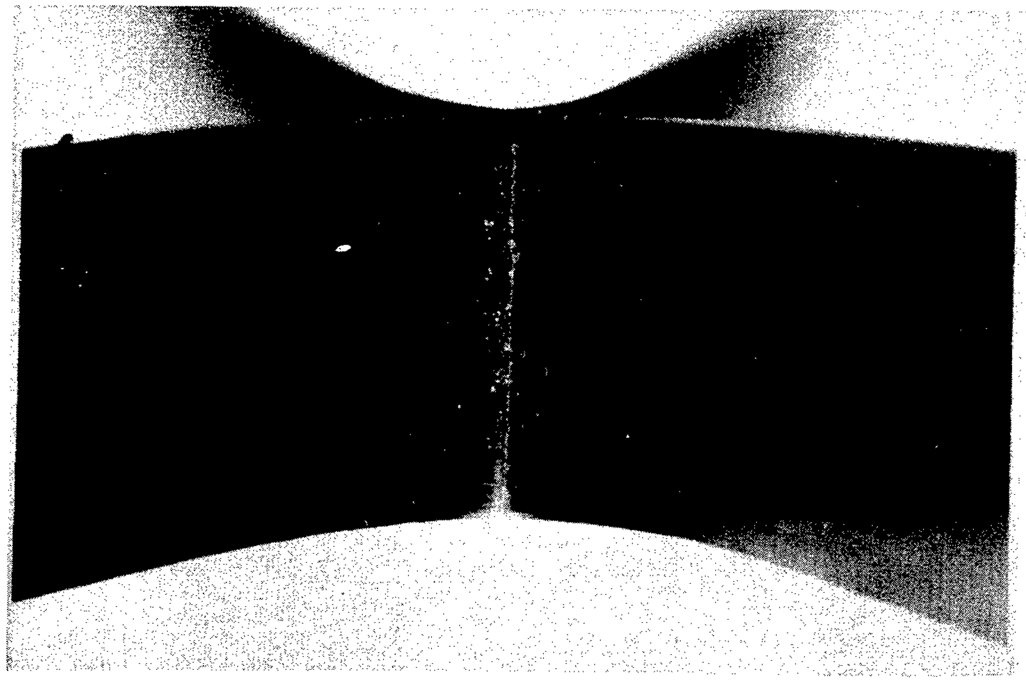
Coating spalled off in full thickness.



Bend Test on 61S Alloy With 0.004-Inch Coating

Coating spalled off over wide area when initial failure occurred. Edge spalling precedes general failure.

Figure 40



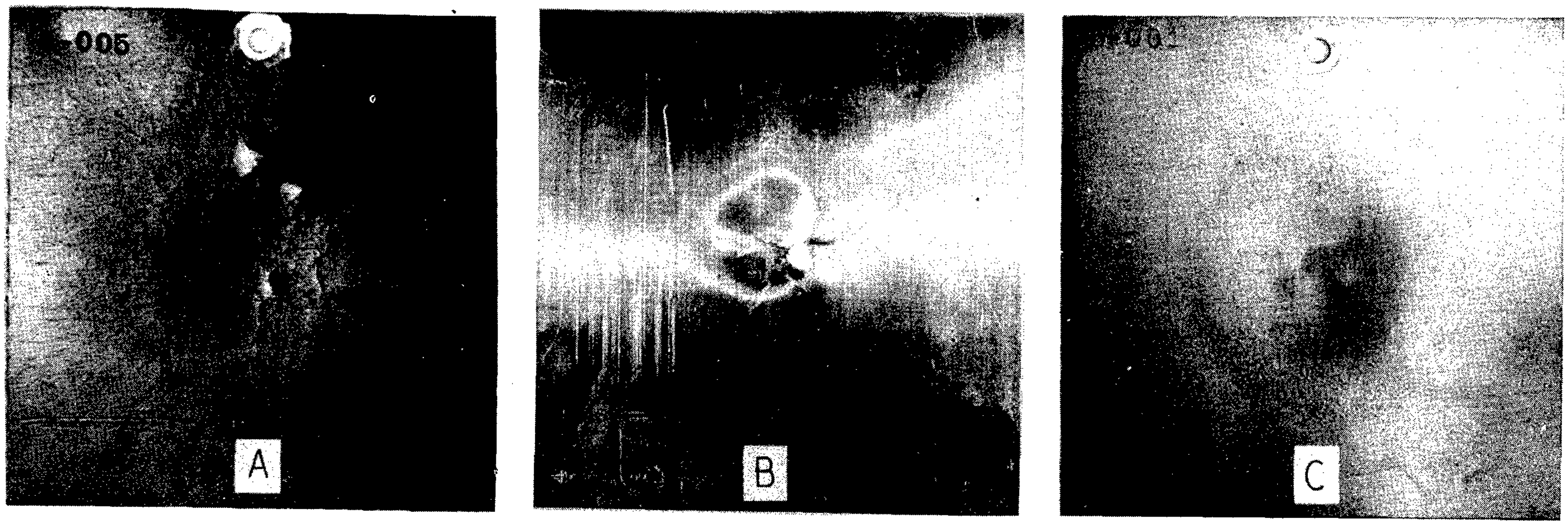
Bend Test on 0.002-Inch Coating on 61S Alloy

Coating failed by hairline spalling on the compression side. The coatings on 75S alloy and XA78S alloy fail in the same manner indicating a tenacious adherence to the base metal.

Figure 41

EXPLANATION OF Figure 42

A	B	C
24S Alclad	24S Alclad	75S
0.005-Inch Coating	Uncoated	0.001-Inch Coating



FLAME TESTS

Condition which was taken as "end-point".

Figure 42

HEAT TESTS

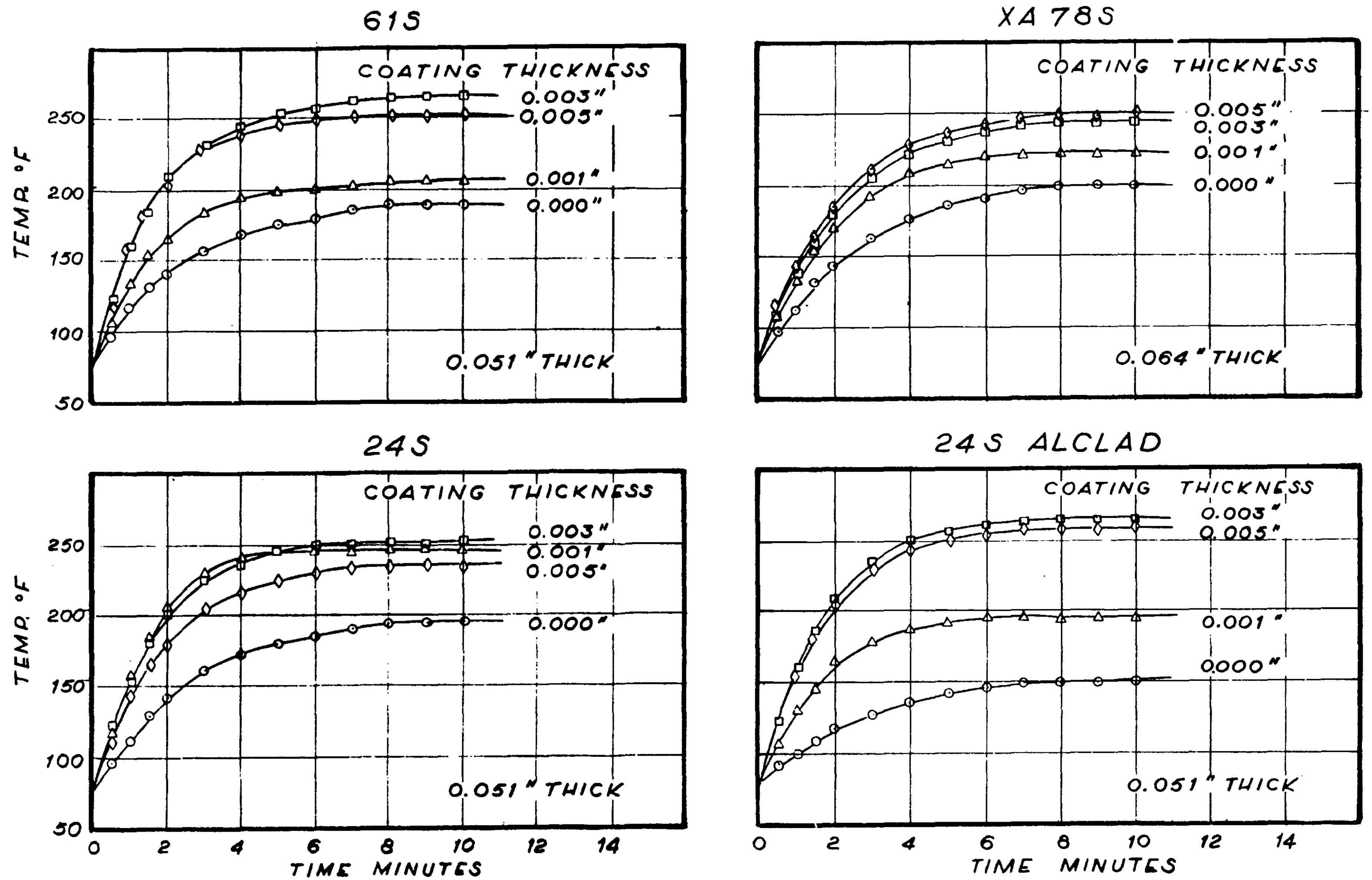


FIG. 43

HEAT TESTS

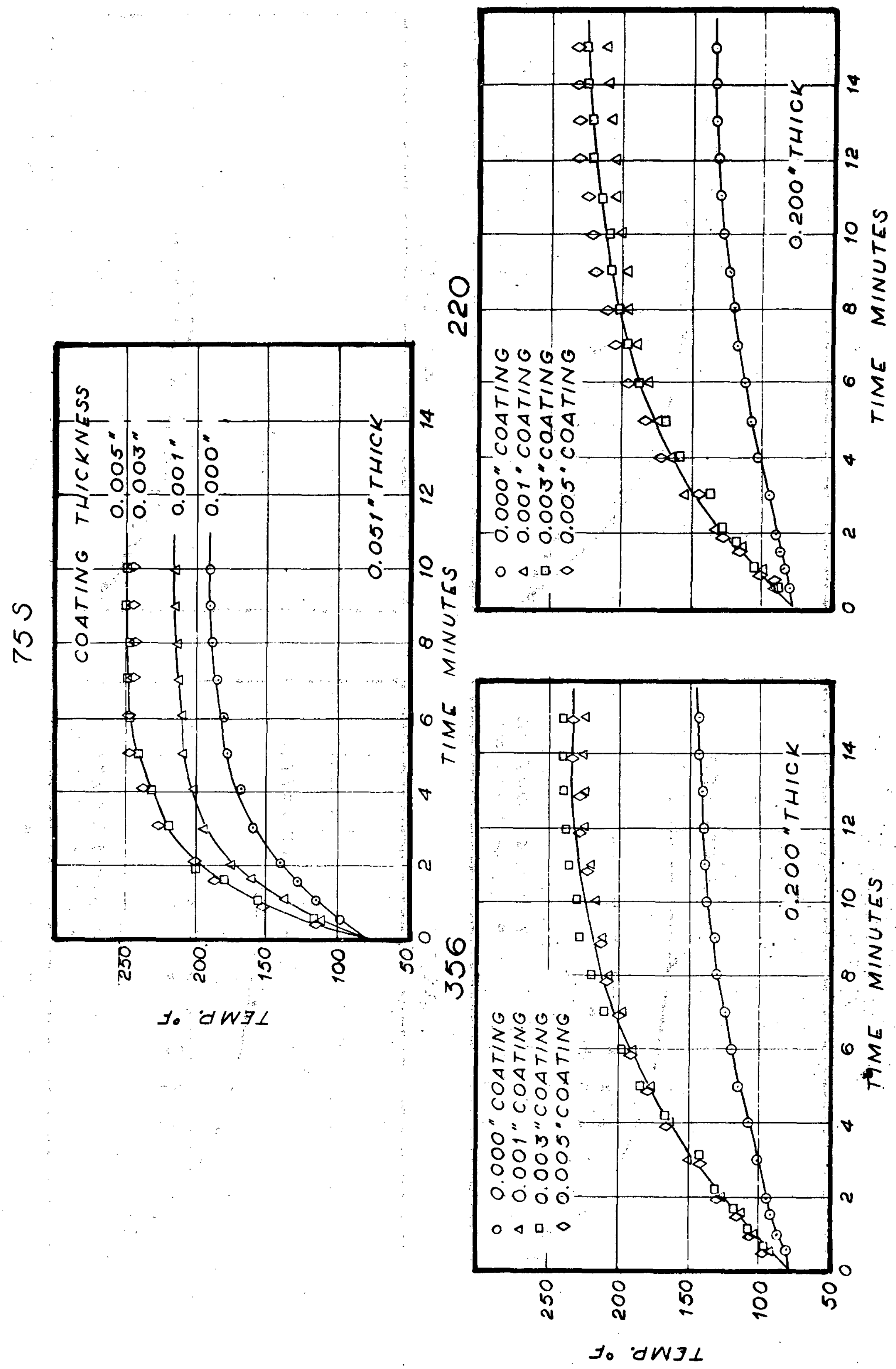


FIG. 44

THERMAL CONDUCTIVITY

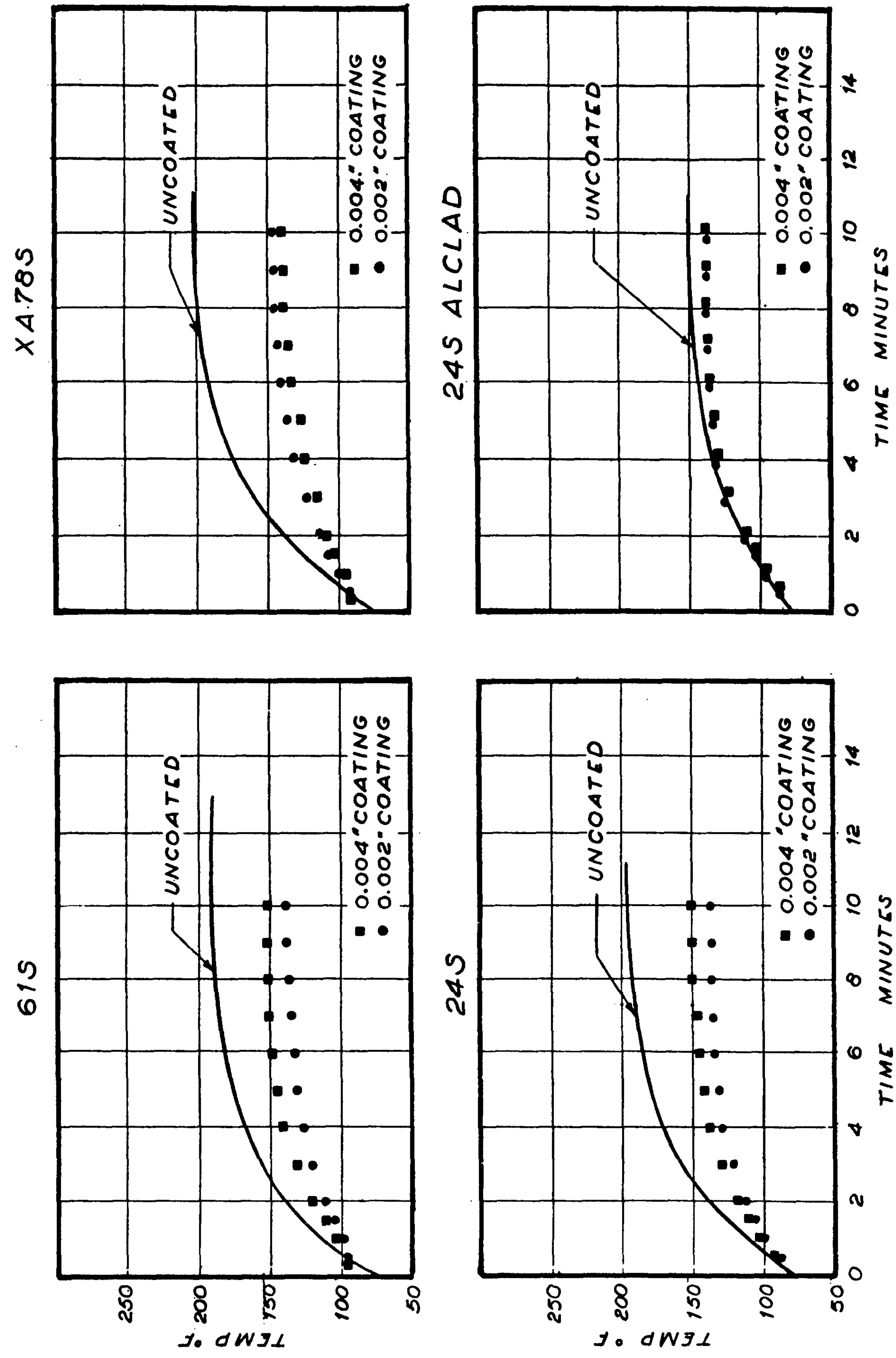


FIG. 45

THERMAL CONDUCTIVITY

75S

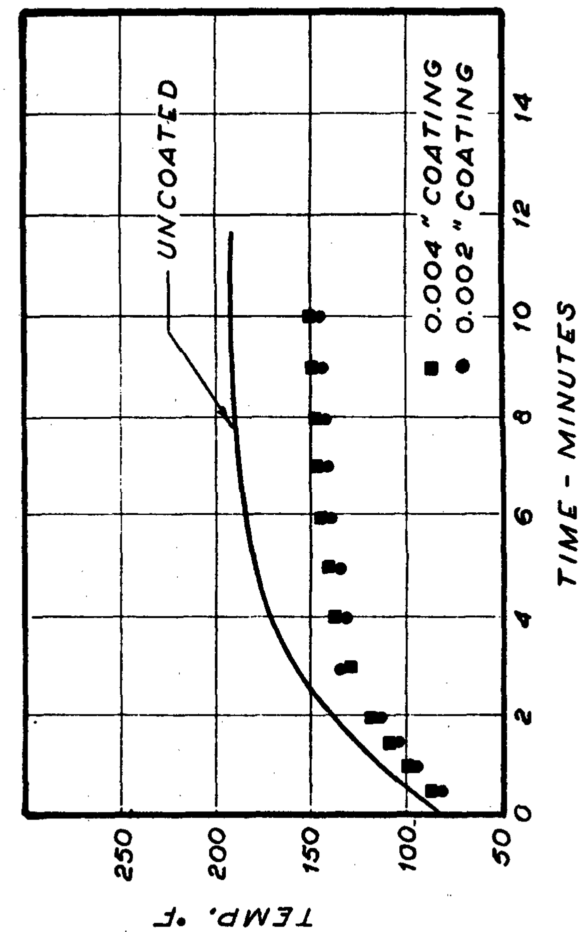


FIG. 46

EFFECTS OF RAIN EROSION ON MARTIN HARDCOAT

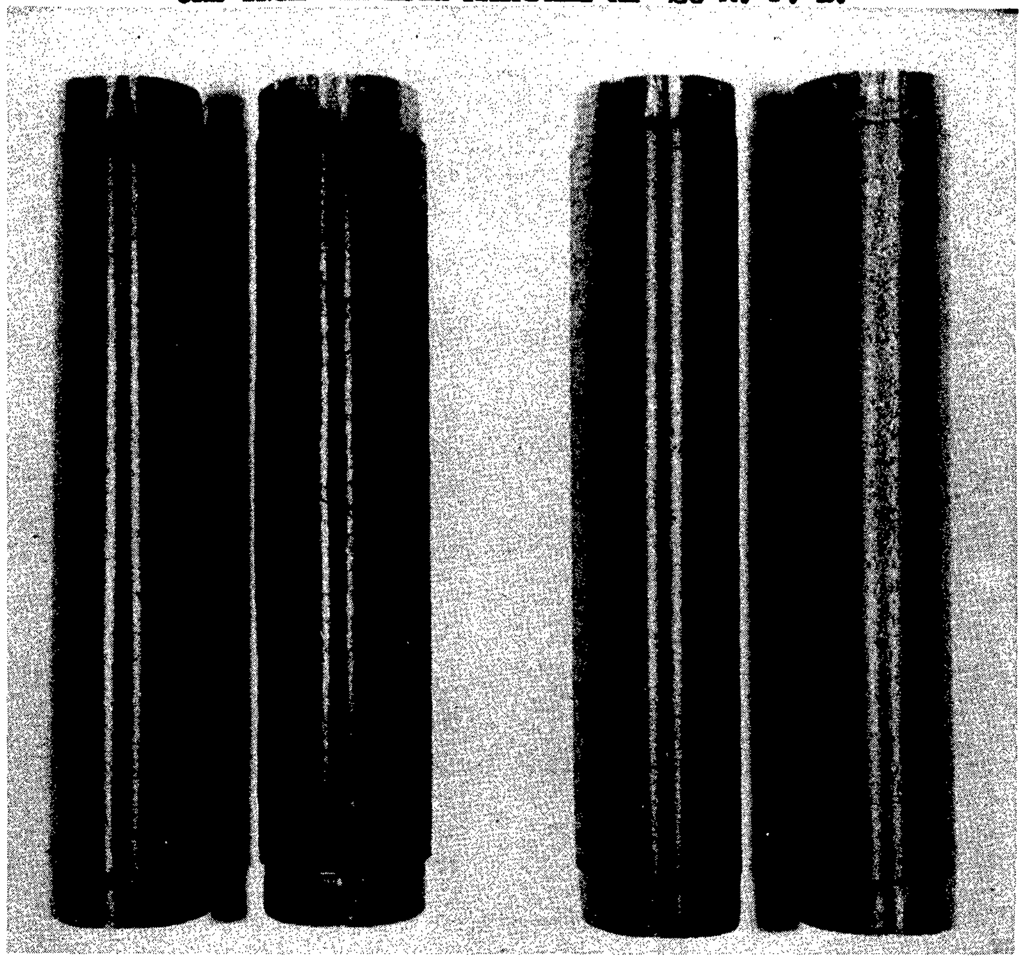
ONE INCH PER HOUR RAINFALL AT 500 M. P. H.

	61S		XA78S		24S	
COATING THICKNESS	0.003"	0.005"	0.003"	0.005"	0.003"	0.005"
TIME OF EXPOSURE	5 MIN.	5 MIN.	5 MIN.	5 MIN.	5 MIN.	5 MIN.

Figure 47 A

EFFECTS OF RAIN EROSION ON MARTIN HARDCOAT

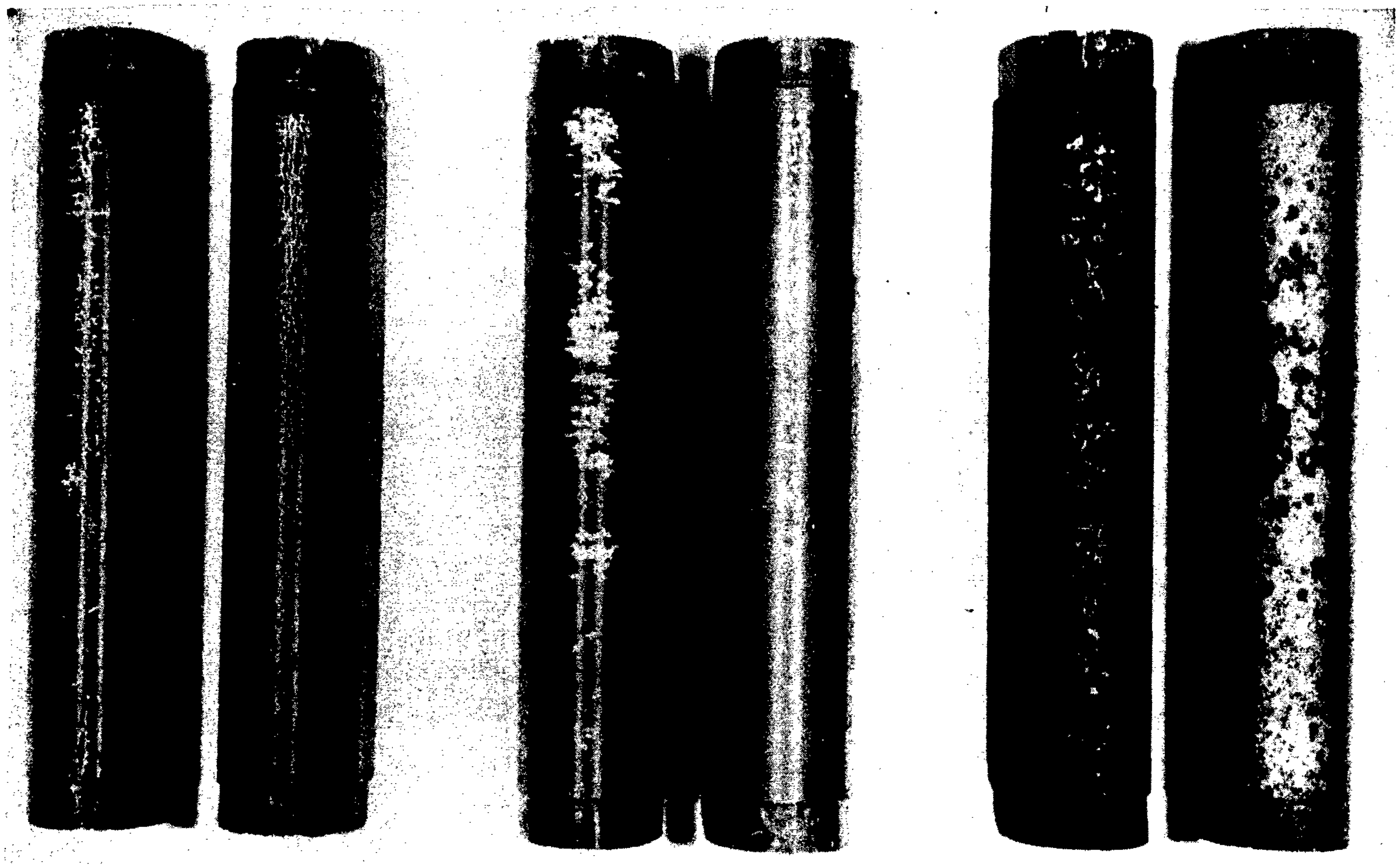
ONE INCH PER HOUR RAINFALL AT 500 M. P. H.



	24S Alclad		75S	
COATING THICKNESS	0.003"	0.005"	0.003"	0.005"
TIME OF EXPOSURE	5 MIN.	5 MIN.	5 MIN.	5 MIN.

Figure 47 B

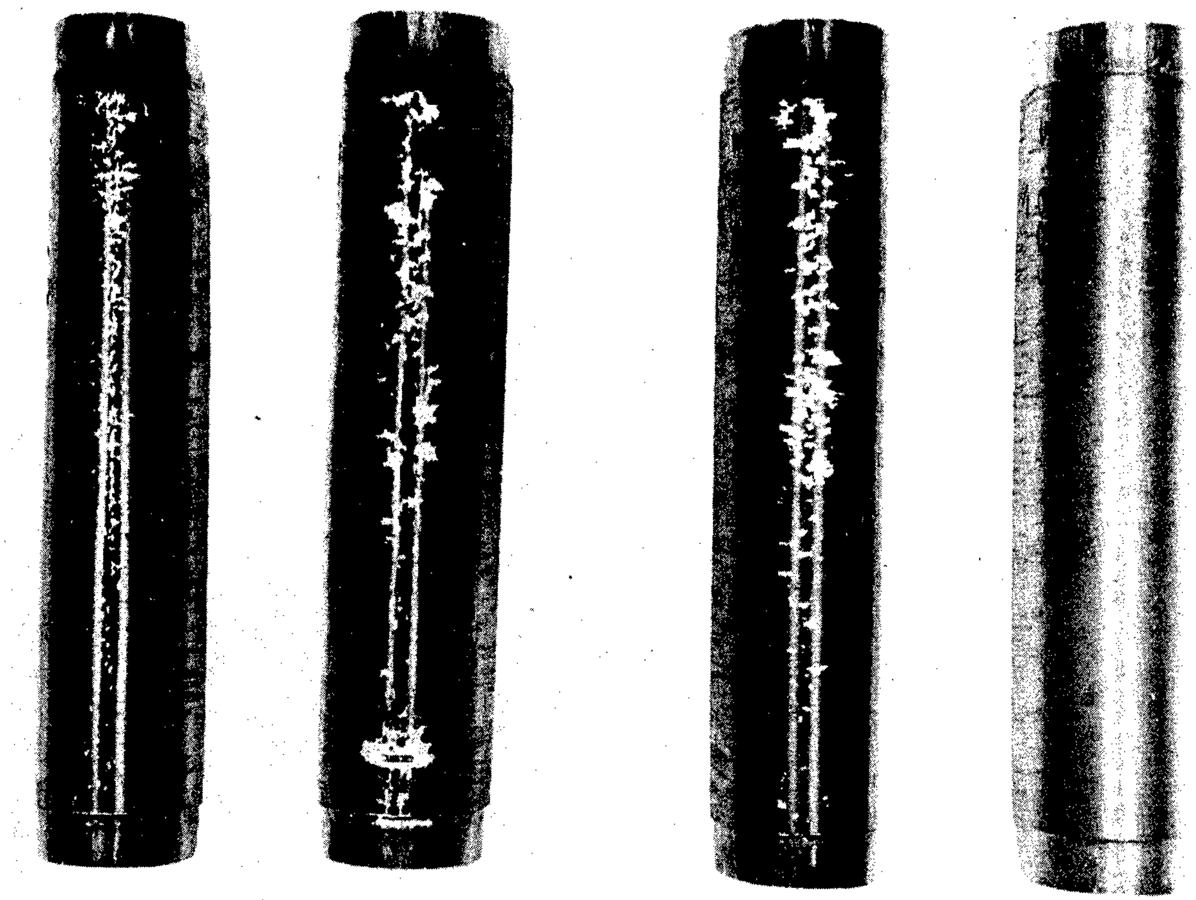
EFFECTS OF RAIN EROSION ON MARTIN HARDCOAT
ONE INCH PER HOUR RAINFALL AT 500 M. P. H.



	61S		XA78S		24S	
COATING THICKNESS	0.003"	0.005"	0.003"	0.005"	0.003"	0.005"
TIME OF EXPOSURE	35 MIN.	25 MIN.	25 MIN.	5 MIN.	5 MIN.	5 MIN.

Figure 48 A

EFFECTS OF RAIN EROSION ON MARTIN HARDCOAT
ONE INCH PER HOUR RAINFALL AT 500 M. P. H.



	24S ALCLAD		75S	
COATING THICKNESS	0.003"	0.005"	0.003"	0.005"
TIME OF EXPOSURE	40 MIN.	20 MIN.	26 MIN.	5 MIN.

Figure 48 B

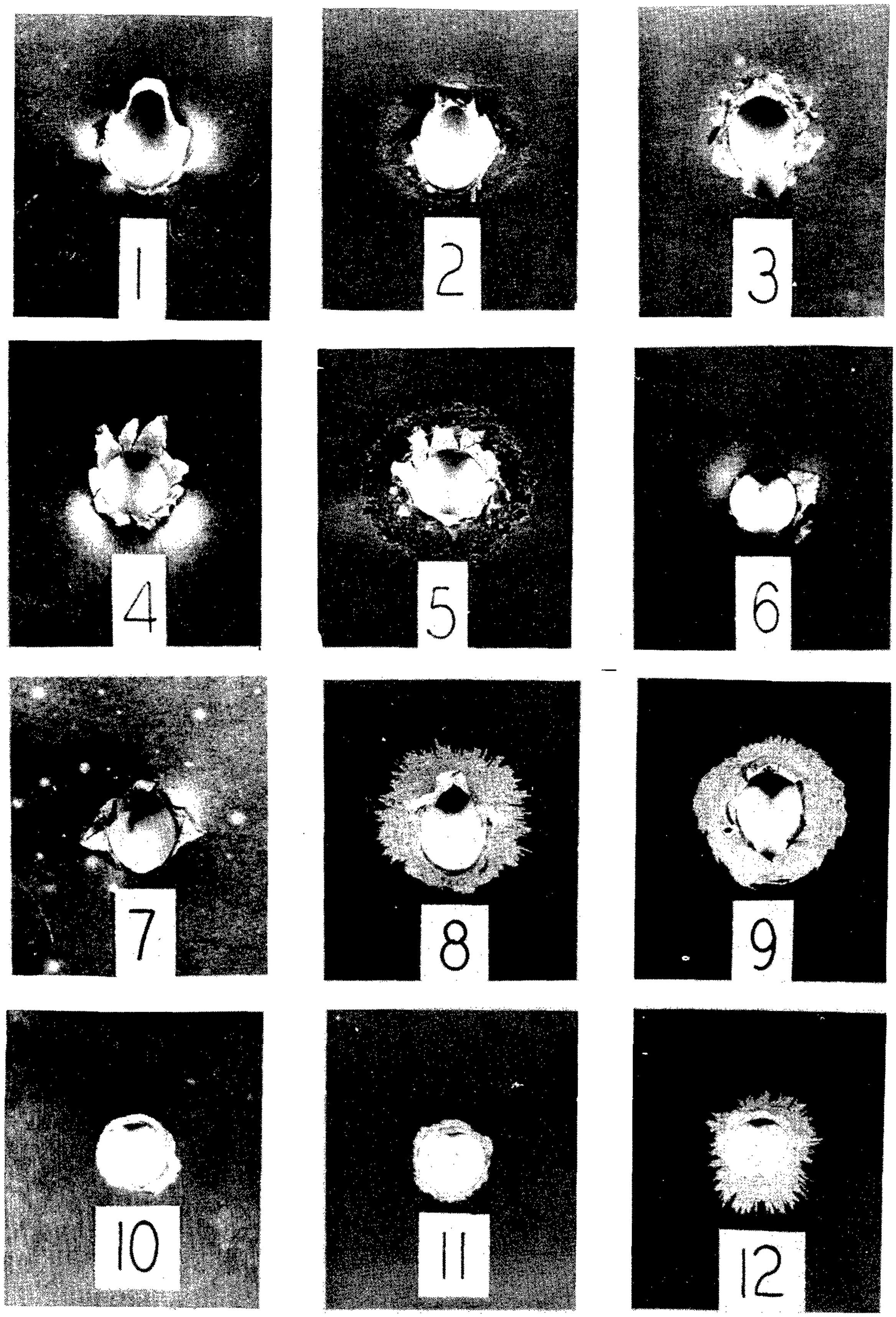
EXPLANATION OF FIGURE 49

Panel No.	1	2	3
Alloy	24S-T4	24S-T4	24S-T4
Coating Thickness - Inches	0.000	0.003	0.003
Angle of Panel	45°	45°	45°
Side Shown	Exit	Exit	Entrance

Panel No.	4	5	6
Alloy	24S-T4	24S-T4	24S-T4
Coating Thickness - Inches	0.000	0.003	0.003
Angle of Panel	90°	90°	90°
Side Shown	Exit	Exit	Entrance

Panel No.	7	8	9
Alloy	75S-T6	75S-T6	75S-T6
Coating Thickness - Inches	0.000	0.003	0.003
Angle of Panel	45°	45°	45°
Side Shown	Exit	Exit	Entrance

Panel No.	10	11	12
Alloy	75S-T6	75S-T6	75S-T6
Coating Thickness - Inches	0.000	0.003	0.003
Angle of Panel	90°	90°	90°
Side Shown	Exit	Entrance	Exit



EFFECT OF GUNFIRE PENETRATION
Figure 49